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Re-Use of Clean Coal Technology By-Products in the Construction of Low Permeability Liners

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ABSTRACT

This final project report presents the results of a research program conducted at The Ohio State University from October 1, 1996 to March 31, 2000 to investigate the use of stabilized flue gas desulfurization (FGD) materials in the construction of low permeability liners. The objective of the research program was to establish field-verified time-dependent relationships for the performance of liners constructed from stabilized FGD by-products generated in Ohio. The project objective was accomplished with a coordinated program of testing and analyzing small-scale laboratory specimens under controlled conditions, medium-scale wetland mesocosms, and a full-scale pond facility. Although the specific uses directly addressed by this report include liners for surface impoundments, the results presented in this study are also useful in other applications including design of daily cover and liners for landfills, seepage cutoff walls and trenches and for nutrient retention and pollution mitigation wetlands.

The small scale laboratory tests, medium scale mesocosm wetland experiments, and construction and monitoring of a full-scale FGD lined facility (capacity of one million gallons) shows that stabilized FGD materials can be used as low permeability liners in the construction of water and manure holding ponds, and constructed wetlands for wastewater treatment. Actual permeability coefficients in the range of 10^{-7} cm/sec (3 x 10^{-9} ft/sec) can be obtained in the field by properly compacting lime and fly ash enriched stabilized FGD materials. Leachate from the FGD material meets Ohio's non-toxic criteria for coal combustion by-products, and for most potential contaminants the national primary and secondary drinking water standards are also met. The low permeability non-toxic FGD material investigated in this study poses very minimal risks, if any, for groundwater contamination. Constructed FGD-lined wetlands offer the opportunity for increased phosphorous retention giving rise to the potential use of these materials as a liners for wastewater treatment wetlands. While plant growth was observed to be less vigorous for FGD lined wetland mesocosms compared to the control, the above and below ground biomass were not significantly different. Cost estimates for FGD liners compared favorably with clay liners for varying haul distances.

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1 INTRODUCTION

1.1 Background and Objectives

In the past two decades, restrictions on the emission of sulfur dioxide from coal-fired power plants have been increasingly stringent in the United States. In response to these developments, power plants have had to remove increasing amounts of SO_2 from the flue gases before releasing them to the atmosphere. This process typically involves the injection of a reagent into the flue gases to form a solid by-product, which can then be collected. This solid by-product is commonly referred to as Flue Gas Desulfurization (FGD) material. Its principal constituents are varying amounts of sulfates and / or sulfites of the reagent, unreacted lime and fly ash. The FGD material may be dry or wet depending on the desulfurization process. The wet scrubbing process, which is commonly used by large electric utilities in Ohio, involves the injection of a reagent (typically hydrated quicklime) into the flue gases. The wet product generated (commonly referred to as FGD filter cake) is a dewatered mixture of sulfites and sulfates of the reagent, unreacted reagent, and some water. Calcium sulfite content is typically greater than 70% while the calcium sulfate content is approximately 13%. Fly ash and additional quicklime are added to stabilize the FGD filter cake. This stabilized (fixated) FGD material is gray in color and looks like silty clay.

In the past, FGD material has generally been treated as a waste product and landfilled. But the increasing cost of landfilling as well as the scarcity of landfill space have led utility companies to look into the beneficial re-use of this by-product. Several researchers at The Ohio State University have led efforts to use FGD materials for land application (Stehouwer et al. 1991, 1998; Dick, 1998). They identified a number of agricultural and engineering properties of both wet and dry clean coal technology by-products. Investigations into the swelling (Adams, 1992), static (Hargraves, 1994; Kim et al., 1995; Chen et al., 1997) and dynamic (Roy, 1994) stress-strain response of these by-products have been carried out. Payette et al. (1997) demonstrated the use of FGD material in the stabilization of a portion of a failed highway embankment. Encouraged by the promising results obtained by the above listed studies, a research program was developed at The Ohio State University to study the suitability of compacted stabilized FGD materials as low permeability liners.

The objective of the research program presented in this report was to establish field-verified time-dependent relationships for the performance of liners constructed from stabilized flue gas desulfurization by-products generated in Ohio. The project objective was accomplished with a coordinated program of testing and analyzing small-scale laboratory specimens under controlled conditions, medium-scale wetland mesocosms, and a full-scale pond facility. Although the specific uses directly addressed by this report include liners for surface impoundments, the results presented in this study will also be useful in other applications including design of daily cover and liners for landfills, seepage cutoff walls and trenches, and for nutrient retention and pollution mitigation wetlands.

1.3 Outline of Report

Chapter 1 presents an introduction to the report. The small-scale laboratory testing program consisting of permeability and strength testing, freeze-thaw cycling experiments, and leaching potential tests are presented in Chapter 2. The construction and monitoring of small-scale FGD lined mesocosms at the Olentangy River Wetland Research Park is discussed in Chapter 3. Chapter 4 presents the design, construction, monitoring, and performance evaluation of the full-scale FGD lined facility (capacity of one million gallons) at the Ohio Agricultural Research and Development Center Western Branch in South Charleston. Chapter 5 includes cost estimates for wetland creation and water supply / manure holding pond and a preliminary market evaluation in vicinity of two Ohio FGD generating facilities. Summary, conclusions, and recommendations for future work are presented in Chapter 6. The report includes a list of reference and several appendices.

2 LABORATORY TESTING PROGRAM

2.1 Introduction

In order to evaluate the potential use of stabilized FGD materials for liner applications, it is important to characterize the material under standard laboratory testing procedures so that the response of the material under a controlled environment can be ascertained. The four main technical issues relating to low permeability FGD liners are permeability, strength, leachate potential, and durability of the material. In this chapter, we present the results of laboratory investigations of the hydraulic conductivity, strength, effect of freeze-thaw cycling and leaching potential of stabilized FGD materials.

2.2 Permeability and Strength

The material used in preparing the samples was generated by American Electric Power's Plant near Conesville, Ohio. At this plant, a lime enriched wet scrubbing process is used to remove the SO_2 from the flue gases. The filter cake (FC) obtained in this process is mixed with Class F fly ash (FA) and lime (L) to produce the stabilized FGD. The FGD material is stored on a temporary curing pad for 3-4 days to reduce the moisture content and allow for some curing. This permits the material to be handled more easily and subsequently it can be hauled to the plant landfill.

2.2.1 Laboratory Mixes

The eight different mixes prepared in the laboratory by mixing varying amounts of fly ash, filter cake, lime and silica fume are shown in Table 2.1. On the basis of plant operating parameters, samples were prepared using two different FA:FC ratios (dry weight basis). The 1:1 mix was representative of the "typical mix" produced by the plant, while the 2:1 mix was a "dryer mix" that the plant could produce occasionally upon request. The typical mix and dryer mix produced by the Conesville plant were reported to have free lime content (percentage weight of free lime based on dry weight of fly ash and filter cake mixture) of approximately 4% and 5% respectively. Based on these lime estimates, the typical mix samples (1:1) were prepared with lime contents of 4% and 8%, while the dryer mix samples (2:1) were made with lime contents of 5% and 8%. The 8% lime content samples were prepared in order to study the effect of increasing the lime content on the engineering properties of the FGD material. The effect of adding 5% silica fume to the design mixes was also studied. Silica fume, a commonly used pozzolan in concrete, primarily consists of amorphous (non-crystalline) silicon dioxide (SiO_2). The samples with the different component combinations were designated as shown in Table 2.1. For example, the 66-34-8-5 sample indicates that 66 parts of fly ash and 34 parts of filter cake were mixed on a dry weight basis along with 8 parts of lime and 5 parts of silica fume.

Relationships between water content and dry density for the laboratory mixes were obtained using the standard Proctor compaction test for 4" (10.2 cm) molds as prescribed by ASTM D698 (1997). The optimum moisture content and maximum dry density obtained in the laboratory for the eight mixes are shown in Table 2.2. The optimum moisture content ranged between 27 and

37%, while the maximum dry density ranged from 10.4 to 12.4 KN/m^3 (66 to 79 lb/ft^3). The lowest optimum moisture content and the highest maximum dry density were achieved for sample 5 which had 2:1 ratio of FA:FC with 5% lime. The lowest maximum dry density was obtained for sample 4 which consisted of equal parts of fly ash and filter cake with 8% lime and 5% silica fume added. Increasing the amount of lime led to an increase in the optimum moisture content while the maximum dry density decreased. Adding silica fume resulted in a significant decrease in the maximum dry density. For the typical mixes (samples 1-4), adding silica fume resulted in slightly lower or no change in the optimum moisture content. On the other hand, the dryer mixes (samples 5-8) showed increased optimum moisture content with the addition of silica fume.

Compacted samples for permeability tests were prepared for all the candidate mixes at moisture contents which were 1-2% higher than the optimum moisture contents. Falling head permeability tests (as per ASTM D5084, 1996; ASTM D5856, 1996) were conducted on the samples at curing times of 7, 28, 60 and 90 days. On the completion of the 90-day permeability test, the samples were tested for unconfined compressive strength. The results of the permeability and compressive strength tests are shown in Table 2.3. The 90-day permeability coefficients measured in the laboratory for samples 6 and 8 were lower than $1x10^{-7}$ cm/sec ($3x10^{-9}$ ft/sec), which is typically recommended by USEPA for constructing liners for waste containment facilities (Goldman, et al., 1988). Even the 60-day permeability value for sample 8 was less than $1x10^{-7}$ cm/sec ($3x10^{-9}$ ft/sec). In general, all the samples showed decreasing permeability with increasing curing time. The addition of extra lime to the samples resulted in a decrease in permeability of the samples for all curing durations especially the 60 and 90-day values (which were reduced by an order of magnitude). The inclusion of silica fume in the samples resulted in only slightly lower permeabilities that would usually not justify the increased cost of using it as an additive to the FGD material. The sample with highest FA:FC ratio and lime content (sample 6) would thus be the obvious choice for constructing a low permeability liner. The unconfined compressive strength of sample 6 at 90 days was measured to be 2.36 MPa (342 psi).

2.2.2 Plant Stabilized Mixes

It needs to be observed that samples 1-8 (refer Table 2.1) were prepared in the laboratory by mixing fly ash, filter cake, lime and silica fume in specific ratios. Since sample 6 (high FA:FC ratio and high lime content) exhibited lowest permeability, it was decided to obtain stabilized FGD materials that had been pre-mixed at the plant from the Conesville and Gavin power plants of AEP. The material so produced would have the highest FA:FC ratio that the plant operations would allow. Two types of high FA:FC ratio plant mixes with low (4%-5%) and high (8%) lime contents as controlled by plant operations were generated at the power plants. After approximately 5 days of curing at the plant, the material was picked up from the plant pad and brought to the laboratory for testing. Permeability samples were prepared for the four mixes at the moisture contents as received from the pad. Table 2.4 shows the samples prepared, their moisture contents, dry densities, 7, 28, 60, and 90-day permeabilities and 90-day unconfined compressive strengths.

The CON(AEP)-5%L and CON(AEP)-8%L samples were obtained from American Electric Power's (AEP) Conesville power plant near Coshocton, Ohio, while the GAV(AEP)-4%L and

GAV(AEP)-8%L samples were obtained from AEP's Gavin plant near Gallipolis, Ohio. 4%L and 5%L denote the lime percentage on a dry weight basis as estimated by the plant operators. The CON and GAV samples were compacted using standard proctor test guidelines (ASTM D698, 1997) at as received moisture contents. It can be observed from Tables 2.2 and 2.4 that moisture contents of the samples received from the power plants were higher than the optimum moisture contents obtained in the laboratory. Consequently, the dry densities obtained by compacting these samples were lower than the maximum dry densities obtained from the laboratory mixed samples. However, the coefficient of permeability, which was measured as a function of curing time (7, 28, 60, and 90 days) using a falling head test (ASTM D5084, 1996; ASTM D5856, 1996) is lower for the plant mixed samples than for the laboratory samples. For the plant mixed samples, the permeability values are in the 10^{-7} cm/sec ($3x10^{-9}$ ft/sec) to 10^{-8} cm/sec ($3x10^{-10}$ ft/sec) range at 28 days of curing. Samples with higher lime contents resulted in lower coefficients of permeability as well as higher unconfined compressive strengths. From Table 2.4 it can be observed that the permeability and strength characteristics of FGD materials generated at the Conesville and Gavin plants are similar. The 8% lime samples have the lowest permeability values that come close to 10^{-8} cm/sec ($3x10^{-10}$ ft/sec). It can be concluded from Table 2.4 that lime and fly ash enriched stabilized FGD material can be compacted in the laboratory using standard soil testing procedures to obtain permeability coefficients that are in the 10^{-8} cm/sec ($3x10^{-10}$ ft/sec) range, which is lower than the $1x10^{-7}$ cm/sec ($3x10^{-9}$ ft/sec) value typically recommended by USEPA for constructing liners for waste containment facilities (Goldman, et al., 1988).

Table 2.1 Laboratory Mixes

Sample Number	Sample Designation FA-FC-L-SF		FA:FC Ratio*	Lime Content** (%)	Silica Fume** (%)
1	50-50-4-0	**Typical Mix**	1:1	4	0
2	50-50-8-0		1:1	8	0
3	50-50-4-5		1:1	4	5
4	50-50-8-5		1:1	8	5
5	66-34-5-0	**Dryer Mix**	2:1	5	0
6	66-34-8-0		2:1	8	0
7	66-34-5-5		2:1	5	5
8	66-34-8-5		2:1	8	5

* Fly ash to filter cake ratio on a dry weight basis
** Percentage based on dry weight of fly ash and filter cake mixture
FA: Fly Ash FC: Filter Cake L: Lime SF: Silica Fume

Table 2.2 Standard Compaction Test Results on Laboratory Mixes

Sample Number	Sample Designation FA-FC-L-SF	Optimum Moisture Content (%)	Maximum Dry Density (KN/m^3)
1	50-50-4-0	32	11.9
2	50-50-8-0	35	11.3
3	50-50-4-5	32	10.9
4	50-50-8-5	32	10.4
5	66-34-5-0	27	12.4
6	66-34-8-0	32	12.2
7	66-34-5-5	36	11.7
8	66-34-8-5	37	12.0

FA: Fly Ash FC: Filter Cake L: Lime SF: Silica Fume
1 KN/m^3 = 6.366 lb/ft^3

Table 2.3 Permeability and Unconfined Compressive Strength Results for Laboratory Mixes

Sample Number	Sample Designation FA-FC-L-SF	Permeability Coefficient (cm/sec)				Unconfined Compressive Strength at 90 days (MPa)
		7 day	28 day	60 day	90 day	
1	50-50-4-0	$2.9x10^{-5}$	$2.6x10^{-6}$	$2.4x10^{-6}$	$2.3x10^{-6}$	0.98
2	50-50-8-0	$3.3x10^{-5}$	$1.6x10^{-6}$	$2.3x10^{-7}$	$1.8x10^{-7}$	1.47
3	50-50-4-5	$7.1x10^{-6}$	$1.5x10^{-6}$	$2.4x10^{-6}$	$2.5x10^{-6}$	-
4	50-50-8-5	$2.3x10^{-5}$	$1.4x10^{-6}$	$1.7x10^{-7}$	$1.6x10^{-7}$	1.77
5	66-34-5-0	$3.6x10^{-5}$	$3.2x10^{-6}$	$1.5x10^{-6}$	$1.4x10^{-6}$	1.66
6	66-34-8-0	$1.4x10^{-5}$	$1.2x10^{-6}$	$1.3x10^{-7}$	$4.8x10^{-8}$	2.36
7	66-34-5-5	$3.3x10^{-6}$	$3.7x10^{-7}$	$3.5x10^{-7}$	$4.4x10^{-7}$	1.37
8	66-34-8-5	$3.5x10^{-6}$	$1.3x10^{-7}$	$3.5x10^{-8}$	$4.5x10^{-8}$	3.95

FA: Fly Ash FC: Filter Cake L: Lime SF: Silica Fume
1 MPa = 145 psi 1 cm/sec = 0.0328 ft/sec

Table 2.4 Permeability and Unconfined Compressive Strength Results for Plant FGD Mixes

Sample Designation	Moisture Content (%)	Dry Density (KN/m^3)	Permeability Coefficient (cm/sec)				Unconfined Compressive Strength at 90 days (MPa)
			7 day	28 day	60 day	90 day	
CON(AEP)-5%L	48	11.1	$2.6x10^{-6}$	$3.6x10^{-7}$	$3.2x10^{-7}$	$2.6x10^{-7}$	1.65
CON(AEP)-8%L	42	11.9	$1.3x10^{-6}$	$6.1x10^{-8}$	$3.4x10^{-8}$	$3.0x10^{-8}$	4.33
GAV(AEP)-4%L	51	10.8	$2.2x10^{-6}$	$2.2x10^{-7}$	$1.5x10^{-7}$	$1.7x10^{-7}$	2.55
GAV(AEP)-8%L	39	12.5	$1.6x10^{-6}$	$1.2x10^{-7}$	$2.0x10^{-8}$	$1.0x10^{-8}$	4.18

AEP: American Electric Power CON: Conesville plant GAV: Gavin plant L: Lime
1 KN/m^3 = 6.366 lb/ft^3 1 MPa = 145 psi 1 cm/sec = 0.0328 ft/sec

2.3 Effect of Freeze-Thaw Cycling

Alternating episodes of freeze and thaw can adversely affect the engineering properties of some FGD materials and hence the durability of the FGD material was a concern. The effect of freeze-thaw cycling on the static strength of stabilized FGD was studied by Hargraves (1994) and Chen *et al*. (1997). They found that if the stabilized FGD material has minimum lime content of 5% and is allowed to cure for 60 days before being exposed to freeze-thaw, the degradation in strength is quite minimal. This recommendation of OSU researchers is now accepted by Ohio Environmental Protection Agency for the construction of FGD engineered structures. In this section, we present the results of a preliminary study investigating the effect of freeze-thaw cycling on the permeability coefficient of the FGD material.

The stabilized FGD material for the study was obtained from the Conesville power plant of AEP. The fly ash to filter cake ratio for the material was estimated to be 0.8:1. The lime content of the material was estimated to be 4% as per plant control operations. Samples were prepared using as received 4% lime content material and adding additional 6% lime to bring the total lime content to 10%. Cylindrical Harvard miniature samples were compacted as per ASTM D698 at as received moisture content of 60%. The test cylinders were allowed to cure for a total of 7, 28, 60, and 90 days. At the completion of the designated curing period, alternating cycles of freeze-thaw were begun as specified in ASTM D560 (1996). In the present study, two modifications to the ASTM standard procedure were made. First, to simulate better the conditions to be expected typical of most Ohio locations, the minimum temperature was set at -18^{o}C rather than -23^{o}C as specified in the standard. Second, the samples were not brushed after each freeze-thaw cycle to preserve their original shape and mass for permeability testing. Each temperature cycle consisted of a 24-hour freeze at –18^{o}C, followed by a 24-hour thaw in the moist cure box at 23^{o}C. The samples were tested for permeability coefficient at 0, 5, and 10, and 15 thermal cycles by conducting falling head tests on the samples in flexible wall permeameters (ASTM D5084, 1996).

The results of the 4% and 10% lime enriched FGD material exposed to freeze-thaw cycling as elaborated above are shown in Tables 2.5 and 2.6, respectively. The samples were tested at 0, 5, and 10 freeze-thaw cycles for permeability coefficient. The 5 and 10 cycle samples tested for permeability (near saturation) were cycled for additional 5 thermal cycles and then tested for permeability. These samples are represented as 5+5 and 10+5 samples in the Tables 2.5 and 2.6. The higher lime content samples exhibited lower permeability coefficient values (in 10^{-6} cm/sec range) compared to lower lime content samples. The permeability coefficient was not significantly affected by the number of freeze-thaw cycles as long as additional water was not added to the sample via an intermediate permeability test. For the 4% lime samples, the effect of adding additional water during freeze-thaw cycling resulted in an increase in the permeability coefficients by one to two orders of magnitude. However, for the 10% lime samples, the permeability, in general, increased by one order of magnitude. Higher lime content of the FGD material resulted in a smaller increase of permeability coefficient value due to freeze-thaw cycling.

Curing of samples did not significantly affect the permeability coefficients because the fly ash to filter cake ratio of the material was low (0.8:1) and its moisture content was quite high (60%). It is the hypothesis of the authors that although enough lime was available in the samples, the fly ash content was low. The laboratory results presented in Tables 2.3 and 2.4 provide evidence for this hypothesis. It can be seen from these Tables that samples with fly ash to filter cake ratio of 2:1 and much lower moisture contents resulted in permeability values in 10^{-7} cm/sec ($3x10^{-9}$ ft/sec) to 10^{-8} cm/sec ($3x10^{-10}$ ft/sec) range. Additional freeze-thaw testing is necessary at higher lime content (8-10%), higher fly ash to filter cake ratio (2:1), and lower moisture content (about 30-45%) so that the effect of thermal cycling on permeability of stabilized FGD material can be accurately characterized.

Table 2.5 Effect of Freeze-Thaw Cycling on Permeability for 4% Lime FGD Samples

Sample	Number of freeze-thaw cycles	Curing Time							
		7 days		28 days		60 days		90 days	
		γ_d (kN/m^3)	k (cm/sec)	γ_d (kN/m^3)	k (cm/sec)	γ_d (kN/m^3)	k (cm/sec)	γ_d (kN/m^3)	k (cm/sec)
4%Lime-0Cycles	0	9.11	$1.27x10^{-5}$	9.21	$2.21x10^{-6}$	9.17	$2.24x10^{-6}$	9.2	$5.29x10^{-6}$
4%Lime-5Cycles	5	8.98	$1.02x10^{-5}$	9.04	$1.13x10^{-5}$	9.06	$9.09x10^{-6}$	9.06	$4.01x10^{-6}$
4%Lime-5+5Cycles	5+5	8.98	Sample too soft	9.04	$2.07x10^{-4}$	9.06	$1.66x10^{-4}$	9.06	$1.01x10^{-4}$
4%Lime-10Cycles	10	9.27	$6.28x10^{-6}$	9.1	$4.86x10^{-6}$	9.05	$5.42x10^{-6}$	9.28	$1.54x10^{-5}$
4%Lime-10+5Cycles	10+5	9.27	$9.34x10^{-6}$	9.1	$1.23x10^{-4}$	9.05	$9.02x10^{-5}$	9.28	$2.95x10^{-5}$

Initial moisture content = 60%
1 KN/m^3 = 6.366 lb/ft^3 1 cm/sec = 0.0328 ft/sec

Table 2.6 Effect of Freeze-Thaw Cycling on Permeability for 10% Lime FGD Samples

Sample	Number of freeze-thaw cycles	Curing Time							
		7 days		28 days		60 days		90 days	
		γ_d (kN/m^3)	k (cm/sec)	γ_d (kN/m^3)	k (cm/sec)	γ_d (kN/m^3)	k (cm/sec)	γ_d (kN/m^3)	k (cm/sec)
10%Lime-0Cycles	0	9.49	$3.75x10^{-6}$	9.25	$1.45x10^{-6}$	9.29	$2.13x10^{-6}$	9.1	$3.38x10^{-6}$
10%Lime-5Cycles	5	9.27	$4.13x10^{-6}$	9.42	$3.75x10^{-6}$	9.22	$1.97x10^{-6}$	9.18	$2.29x10^{-6}$
10%Lime-5+5Cycles	5+5	9.27	$1.76x10^{-5}$	9.42	$1.32x10^{-4}$	9.22	$1.15x10^{-5}$	9.18	$8.85x10^{-5}$
10%Lime-10Cycles	10	9.33	$5.33x10^{-6}$	9.30	$6.30x10^{-6}$	9.20	$2.71x10^{-6}$	9.14	$3.76x10^{-6}$
10%Lime-10+5Cycles	10+5	9.33	$2.39x10^{-5}$	9.30	$2.58x10^{-5}$	9.20	$3.90x10^{-5}$	9.14	$3.03x10^{-5}$

Initial moisture content = 60%

1 KN/m^3 = 6.366 lb/ft^3 1 cm/sec = 0.0328 ft/sec

2.4 Leaching Potential

The leaching potential of the stabilized FGD material was evaluated using standard 20:1, 18 hour leaching tests as per USEPA Toxicity Characteristic Leaching Procedure (TCLP) dilute acetic acid method 1311 (United States Environmental Protection Agency, 1991). Two liters of the extractant was added to 100g of FGD material in a Teflon bottle. The extractant consisted of 5.7 ml of glacial acetic acid diluted to 1 litre with de-ionized water (pH = 2.88±0.05). Bottles were placed on a rotary shaker (30 rpm) for 18 hours at 25^{o}C. Leachates were filtered and analyzed for pH, total dissolved solids, acidity, alkalinity, conductivity, and 20 elements by ICP and graphite furnace atomic absorption (GFAA) spectrophotometry.

A total of five stabilized FGD material samples from Conesville power plant were collected over a four-week period, and analyzed according to USEPA TCLP Method 1311. The results are presented in Table 2.7. For constituent, its range and mean value were calculated and are reported in Table 2.8. The Table also presents a comparison of the TCLP results with appropriate regulatory levels. Two types of regulatory levels are listed for comparison. First, Ohio EPA's non-toxic criteria (DSW 0400.007, 1994), which is generally 30 times selected national primary drinking water standards, is the regulatory level needed for the FGD material to be considered as non-toxic in the state of Ohio. Second, the national drinking water standards are also listed in Table 2.8. These consist of the National Primary Drinking Water Regulations (NPDWR or primary standards) and the National Secondary Drinking Water Regulations (NSDWR or secondary standards). The primary standards are legally enforceable standards that apply to all public water systems that protect drinking water quality by limiting the levels of specific contaminants that can adversely affect public health. The secondary standards are non-enforceable non-health related guidelines regulating contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as color, odor, or taste) in drinking water.

It can be observed from Table 2.8 that the FGD leachate data for various constituents studied do not vary over a wide range and are bracketed within a reasonably small range of values. The mean values calculated for the potential contaminants are very low. A comparison of the FGD leachate data with Ohio EPA non-toxic beneficial use policy (DSW 0400.007, 1994) shows that for the contaminants studied, the FGD material meets all the criteria specified by the Ohio EPA beneficial use policy by a large factor of safety and hence the stabilized FGD material used in the study can be characterized to be non-toxic. The range and mean values for all constituents are lower than the primary standards (NPDWR). As an example, for Arsenic, the concentration values ranged from 0.004 to 0.008 mg/l with a mean value of 0.006 mg/l, which is less than one-eighth the primary standard value of 0.05 mg/l. Hence, the leachate from stabilized FGD material studied in this investigation meets all the National Primary Drinking Water Regulations. In general, the FGD leachate concentration levels are also lower than the secondary (non-health and unenforceable) standards. The exceptions being pH (mean value of 11.08) and Aluminum (mean value of 5.114 mg/l). The TCLP testing program conducted on the stabilized FGD material indicates that the stabilized FGD material tested in the laboratory is a relatively clean material, non-toxic and poses very minimal risks, if any, for groundwater contamination.

Table 2.7 Modified TCLP Results

Analyte	Units	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Acidity	mg/L	<1	<1	<1	<1	<1
Alkalinity	mg/L	198	174	268	149	212
Aluminum	mg/L	5.54	5.72	4.66	4.37	5.28
Arsenic	mg/L	0.005	0.008	0.004	0.005	0.008
Barium	mg/L	0.188	0.047	0.204	0.151	0.214
Beryllium	mg/L	< 0.0002	<0.0002	< 0.0002	< 0.0002	< 0.0002
Cadmium	mg/L	< .0005	0.001	< 0.0005	0.001	< 0.0005
Chloride	mg/L	36	46	30	34	43
Chromium	mg/L	0.004	0.002	0.002	0.004	0.002
Conductivity	umhos/cm	946	950	1320	828	1120
Copper	mg/L	< 0.001	< 0.001	0.003	< 0.001	< 0.001
Flouride	mg/L	0.2102	0.1387	0.2102	0.1605	0.2129
Iron	mg/L	0.03	0.01	0.02	0.02	< 0.01
Lead	mg/L	< 0.002	< 0.002	< 0.002	< 0.002	<0.002
Manganese	mg/L	< 0.01	<0.01	< 0.01	< 0.01	< 0.01
Mercury	mg/L	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002
Nickel	mg/L	< 0.003	0.014	< 0.003	< 0.003	< 0.003
pH	s.u.	11.0	11.0	11.2	11.0	11.2
Filterable TDS	mg/L	430	402	447	404	450
Selenium	mg/L	0.014	0.007	0.006	0.008	< 0.005
Silver	mg/L	<0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002
Sodium	mg/L	10.5	11.1	9.1	9.6	12.2
Sulfate	mg/L	79	71	49	94	68
Vanadium	mg/L	0.028	0.033	0.021	0.029	0.03
Zinc	mg/L	0.025	0.022	0.028	0.024	0.029

Table 2.8 Comparison of Modified TCLP Results with Regulatory Standards

Constituent	Units	Range for FGD materials tested	Mean value for FGD materials tested	Ohio EPA Non-Toxic Criteria (DSW 0400.007, 1994)	National Drinking Water Standards
Acidity	mg/L	-	<1	-	-
Alkalinity	mg/L	149 - 268	200	-	-
Aluminum	mg/L	4.37 - 5.72	5.11	-	0.05 - 0.2**
Arsenic	mg/L	0.004 - 0.008	0.006	1.5	0.05*
Barium	mg/L	0.047 - 0.214	0.161	60	2*
Beryllium	mg/L	-	< 0.0002	-	0.004*
Cadmium	mg/L	< 0.0005 - 0.001	-	0.15	0.005*
Chloride	mg/L	30 - 46	38	-	250**
Chromium	mg/L	0.002 - 0.004	0.003	3	0.1*
Conductivity	umhos/cm	828 - 1320	1033	-	-
Copper	mg/L	-	< 0.001	-	1.0**
Fluoride	mg/L	0.1387 - 0.2129	0.1865	-	4.0* , 2.0**
Iron	mg/L	< 0.01 - 0.03	<0.018	-	0.3**
Lead	mg/L	-	<0.002	1.5	0.015***
Manganese	mg/L	-	< 0.01	-	0.05**
Mercury	mg/L	-	< 0.0002	0.06	0.002*
Nickel	mg/L	<0.003 - 0.014	-	-	-
pH	s.u.	11.0 - 11.2	11.08	-	6.5 - 8.5**
Filterable TDS	mg/L	402 - 450	427	-	500**
Selenium	mg/L	< 0.005 - 0.008	< 0.008	1	0.05*
Silver	mg/L	-	< 0.0002	-	0.1**
Sodium	mg/L	9.1 - 12.2	10.5	-	-
Sulfate	mg/L	49 - 94	72	-	250**
Vanadium	mg/L	0.021 - 0.033	0.028	-	-
Zinc	mg/L	0.022 - 0.029	0.026	-	5.0**

* : National Primary Drinking Water Regulation (NPDWR)
** : National Secondary (Non-health related) Drinking Water Regulation (NSDWR)
***: Action Level

3 MEDIUM-SCALE MESOCOSM EXPERIMENTS

3.1 Introduction

The retention of nutrients such as phosphorus and nitrogen is one of the most well-known functions of wetlands constructed for water quality improvement (Nichols, 1983; Mitsch and Gosselink, 1993; Kadlec and Knight, 1996). Recently, the construction of wetlands for wastewater treatment including acid mine drainage and agricultural runoff has been more common. Constructed wetlands have been shown in a number of situations to be low-cost structures for controlling wastewater pollution when naturally low-permeability clays are plentiful. But, often, it is practical to have them where no naturally low-permeability clay exists. Thus, artificial liners must be used.

The construction of artificial wetlands for wastewater treatment often needs low-permeability clays for their liners. Liners or relatively impervious site soils are very important to the success of constructed treatment wetlands in areas where ground water levels are typically below the ground surface (Kadlec and Knight, 1996). Most soil, except excessively drained sands and gravels, can be loaded with enough water to result in saturated conditions and establishment of wetland vegetation (Kadlec and Knight, 1996). However, if water inflow column is limited or if the flow will be periodic, an undrained constructed treatment wetland can be desiccated and unable to support wetland vegetation. If site soil naturally has low permeability (clays, fine silts, and clayey loams) due to site topography, liners are not necessary for constructed treatment wetland success. But it is not easy to have plentiful natural clays where the wetlands are to be constructed.

3.2 Background Information

When necessary to hold water or to protect groundwater quality, the most frequently used liners for treatment wetlands are imported clays, clay bentonite mixtures, polyvinylchloride (PVC), and high-density polyethylene (HDPE) synthetic materials (Kadlec and Knight, 1996). Synthetic liners must be well protected from construction and root development damage by overlying soils or gravels (typically 0.3 to 1 m). Synthetic liners are expensive and are prone to more damage than clay or clay-bentonite liners (Kadlec and Knight, 1996). Substrata tried in constructed wastewater treatment wetland include local gravel, soil/sand and peat as well as bentonite, asphalt, concrete, granite, limestone, gold slime waste, crushed rock and power station fly ash (Steiner and Freeman, 1989; Wood and Hensman, 1989; Batchelor et al., 1990; Mann, 1990; Wood, 1990).

Stehouwer et al. (1995) examined the potential use of FGD material for the reclamation of acidic mine spoils and observed no phytotoxicity of the FGD material on plant growth. They found that when applied in amounts equivalent to spoil neutralization needs, dry FGD by-products can benefit acidic soil revegetation with little potential for introduction of toxic elements into the food chain. Stehouwer et al. (1996) also evaluated FGD by-product as effective substitutes for agricultural limestones with little potential for adverse environmental impacts through greenhouse experiments using alfalfa (*Medicago setiva*, L).

Fly ash has been reported for its capacity to retard phosphorus release from lake sediment (Theis and Peter, 1978). Usually lake sediments are known to act as significant sources of phosphorus even after eternal sources have been eliminated. Theis and Peter (1978) found that the application of fly ash as a phosphorus sealant of eutrophic lake sediments effectively brought about reduced release of phosphorus during anoxic periods. The use of coal combustion by-products was also investigated to remove phosphate from water column (Hisashi et al., 1986; Mann and Bavor, 1993). Substratum adsorption is suggested as a significant mechanism in phosphorus removal in a constructed wetland system (Steiner and Freeman, 1989; Mann, 1990; Wood, 1990). Mann (1990) also suggested that substratum should be selected which have a high phosphorus adsorption capacity. Mann and Bavor (1993) examined the phosphorus removal efficiency of constructed wetland systems lined with gravel or industrial by-products such as boiler slag and fly ash by-products in a two-year study in which secondary sewage effluent was treated. Phosphorus adsorption was variable and indicated that further investigations into the inclusion of industrial waste substrata in a constructed wetland system were warranted to optimize phosphorus removal, prior to full-scale construction.

Some previous researches done through mesocosm experiments have offered a means of predicting the effectiveness of the wetland at removing nutrients and metals (Johengen and Paul, 1993; Max et al., 1992; Wieder et al., 1990; Busnardo et al., 1992) and others have showed the usefulness of mesocosm experiments in the research of wetland function (DeSzalay et al., 1996) and in restoration works (Callaway et al., 1997). One of the long-range plans for the Olentangy River Wetland Research Park (ORWRP) at The Ohio State University is to set up experimental mesocosms in replication to investigate, with scientific rigor, questions that arise on the design, construction, or function of wetlands (Laspidou et al., 1994). Mesocosm are miniature ecosystems. In all of these studies, the use of mesocosms allowed statistical replication so that stronger conclusions could be drawn.

In the present study, mesocosm experiments were conducted to investigate the potential effects of stabilized FGD liner materials in constructed wetlands on water quality, plant growth, and nutrient composition. The study provides useful information on water quality of constructed wetlands lined with FGD by-product and presents the results of nutrient analyses and physicochemical investigation of leachate and outflow water samples collected from the mesocosm experiments. The objectives of the mesocosm study were to, 1) investigate the effects of FGD by-product on water quality in wetland systems, 2) investigate the effects of FGD by-product on ecosystem health, e.g. plant growth, and 3) understand the dynamics of the wetland system having FGD liner through the development of ecological model.

3.3 Mesocosm Description and Treatment

In March 1997, a set of 20 flow-through mesocosms (1 m x 1 m x 0.6 m polyethylene tubs) were positioned at the ORWRP, which is a 22-acre research site located on the Columbus campus of The Ohio State University, to investigate the effect of FGD liner on ecological functions of constructed wetlands. Stabilized FGD by-products were randomly assigned to the mesocosms, which resulted in half of them with no FGD liner in the tubs as control (Figure 3.1). Mesocosms were completely buried into the ground to insulate against freezing. Each mesocosm received 10 cm of non-calcareous river pea gravel (completely covering the drain to the standpipe) overlain by 10 -15 cm of field compacted stabilized FGD by-product generated from AEP's Conesville electric power plants, on top of which 15-20 cm of soil obtained during the excavation of the mesocosm site was placed (Figure 3.1). The FGD by-product used in the experiment had an estimated fly ash to filter cake ratio of 1.25 :1 and a lime content of 5 %. The chemical composition of the stabilized FGD material used is shown in Table 3.1. The FGD by-product placed on the mesocosms was compacted in each mesocosm, but soil was not compacted and substantial settling of the soil was observed. Microtopographic variations (1 -3 cm) within the mesocosms were observed after wetting although the bottom was smoothed with hand.

3.4 1997 Experiments

3.4.1 Mesocosm Hydrology

A water delivery system was constructed which would simulate natural flows of contaminated surface runoff into natural or constructed wetlands. This was accomplished through a series of manifolds and valves, which distributed similar volumes of water pumped from the Olentangy River to each of the twenty mesocosms. This water, which is contaminated mostly by agricultural runoff, was first stored in two 425 gallon tanks. These tanks were connected in such a way that they could be isolated or run in series. This allowed the chemistry of the water delivered to half of the mesocosms to be varied, while using the other half as a control. Water levels and the resulting flow to the mesocosms were constantly maintained by a mercury float switch. A # 20 mesh pre-filter was installed and cleaned daily during data collection to prevent clogging in the numerous pipes and valves involved in the water distribution system (Figure 3.2). A continuous inflow rate of 70 ml /minute was chosen as the target inflow rate into each mesocosm during the growing season. This rate is scale simulation of the ORWRP experimental wetlands, which are also fed by river water and have an average inflow of approximately 150 gallons per minute. It was found that steady flow rates from a continual flow system at this scale was difficult to maintain. To solve this problem, a pulse system was used which delivered a similar, per-day volume, but instead flowed rapidly for one hour per day. A common sprinkler system timer was used to uniformize the pulse time and duration. Water level and water flow were measured for maintaining uniform hydrology throughout the 20 mesocosms with no difference between liner and no-liner treatments. Water levels were checked three times a week during the growing season experiment and flow rates of river water into the mesocosms were also measured with a graduated cylinder and a timer. It was difficult to achieve a uniform inflow for each mesocosm in the growing season experiment, but the hydrology between liner and no-liner mesocosms were similar. The comparison of hydrology between the treatments did not show any significant difference ($p = 0.45$ for growing season measured by water level and $p = 0.82$ for non-growing season measured by water flow rate) (Figure 3.3). The hydrology difference measured by water level or water flow rate among each of the 20 mesocosms was within 20 % .

3.4.2 Planting and Survey

Macrophytes were planted on May 17, 1997. Three *Scirpus tabernaemontani* rhizomes were introduced into each of 20 mesocosms. Rhizomes were equally spaced lengthwise in the mesocosm, and pressed just below the surface of moist soil. Rhizomes were shallowly buried (3 cm depth), then the water levels in the mesocosms were adjusted by adding sufficient water to each mesocosm to cover the soil with approximately 10 cm of standing water. These water depths were changed by the introduction of inflow with the start of the experiment.

The experiment was conducted for four weeks during the growing season (July – August 1997) and for another four weeks in the non-growing season (October, 1997). Three items such as number of stems, number of stems bearing flowers and stem length were investigated weekly on every mesocosm during the growing season experiment and once in the middle of non-growing season. In case of stem length, randomly chosen 20 stems were measured for each mesocosm with stick ruler. Number of stems bearing flowers was investigated only during the growing season due to the loss of flowers or unrecognizably withered flowers in non-growing season.

3.4.3 Field Sampling and Analysis Procedures

In growing season, three times-per-week water sampling was done for four weeks. Surface outflows were collected directly from the mesocosm outlets and leachates were obtained from the standpipe connected to the bottom layer of the mesocosms. Two mesocosms, which were not hydrologically sound in leachate collection due to the lack of leachate coming up in the standpipe, were removed from the study. Therefore, only 18 mesocosms were included in the leachate analysis and all of 20 mesocosms were included in the analysis of outflow. Water samples were collected in 500 ml polyethlene bottles. Prior to sample collection, all bottles were hand-washed with 50 % HCl followed by a thorough triple rinse with distilled water. Sample bottles were transported to the field in a cooler and all samples were kept in a freezer at 4 °C until analysis. One sample was filtered through 0.45 μm filter and placed in a freezer for orthophosphate analysis. Filters were soaked for approximately 24 hr in distilled water to remove contamination. The others were preserved by acidification with 2 mL 36 N H_2SO_4 per L of sample (to pH < 2) immediately upon return to the Ecosystem Analytical Laboratory at OSU. A Hydrolab H20G Multiparameter Water Quality Data Transmitter was used to collect pH, conductivity, dissolved oxygen, temperature and oxidation-reduction potential measurements through the period of experiment except the first two weeks of non-growing season due to the H20G malfunctioning. The H20G was calibrated on a weekly basis during the experiment.

Turbidity was determined on the day of sampling with a Hach Model 18900 Ratio Turbidimeter. Nitrate samples were also analyzed on the day of sampling for growing season experiment with Solamet 520 C monitor and Orion ion selective electrode (APHA, 1992) and the samples for non-growing season were frozen and analyzed later by a Latchat QuickChem IV Flow Injection Analysis (FIA) System with total phosphorus (Prokopi, 1993) and orthophosphate (Diamond, 1994) in water samples. All samples and standards were at room temperature and were vigorously mixed by inversion for analysis. Five prepared standards, a check standard and distilled water blank were run each time an analysis was conducted. Standards were always within 10 % of the prescribed values.

Averages of the parameters measured in both ten FGD liner and ten no-liner mesocosms were calculated and compared via two sample unpaired t-test assuming unequal variance. Analyses were run for each sampling days and for each sampling season using the statistical software package, Minitab.

3.4.4 Results and Discussion

3.4.4.1 Conductivity

Conductivity data for growing season experiment showed no significant difference between liner and no-liner treatment, but the conductivity of leachates diverged over time and showed significantly higher values in the leachate from FGD liner mesocosms in the non-growing season (Figure 3.4). In the case of surface outflow, no differences were observed between the treatments for the growing season; data for the non-growing season is not available statistically (Figure 3.5).

3.4.4.2 pH

The pH values of leachates in FGD liner mesocosms were significantly different from those in no-liner mesocosms ($p < 0.01$) (refer to Figure 3.6). The liner mesocosms showed much higher pH throughout the experiments. The difference could be observed between the treatments even in the stabilized values of pH in the non-growing season. This indicates the alkaline nature of the

FGD material and the possibility of using it to treat acid mine drainage. Surface outflow pH values between the treatments were statistically equivalent (Figure 3.7).

3.4.4.3 Redox

As the experiment developed, the redox values of the leachate became more and more reduced as expected with no difference between the liner and no-liner mesocosms in both seasons (Figure 3.8). In the non-growing season, most of the mesocosms showed redox values under 100 mV where nitrogen, iron and manganese are known to exist in reduced forms. A black color coating developed inside the standpipes where leachate samples were collected, probably due to the oxidation of manganese contained in the FGD by-product (Table 3.1). This lowered redox is thought to have stimulated nitrate removal in the leachate through denitrification. The nitrate concentration of leachate in the non-growing season was almost zero. Usually, nitrate becomes reduced and is lost into the atmosphere by denitrification when the redox potential is below 225 mV (Mitsch and Gosselink, 1993).

3.4.4.4 Turbidity

Outflow samples were investigated for turbidity (Figure 3.9). Turbidity decreased significantly from inflow to outflow in all 20 mesocosms ($p < 0.01$) during the growing season, showing the same tendency observed from the two experimental basins of ORWRP (Nairn and Mitsch, 1997). The data showed the same tendency in the non-growing season even though sufficient data were not available for statistical analysis.

3.4.4.5 Total phosphorus

Total phosphorus concentrations were measured for surface outflow and leachate samples from the mesocosms in both seasons (Figures 3.10 and 3.11). The average inflow concentration was greater than the average outflow concentration in every wetland during the growing season ($p < 0.01$), but little difference between inflow and outflow was seen in the non-growing season. Differences between the liner treatments and control were not observed in surface outflows or leachate.

3.4.4.6 Orthophosphate

Orthophosphate concentrations were also measured for all outflow and leachate samples to evaluate the effect of FGD liner on water quality improvement (Figures 3.12 and 3.13). More effective Ca-P precipitation was expected since the FGD liner contains more Ca in its composition than natural clay soils (Nairn, 1996). The results showed significant differences between the liner treatments in leachates during the growing season ($p < 0.01$). More orthophosphate removal was observed in the mesocosms containing FGD liner. Compared to inflow concentrations, all outflows showed significant reduction in phosphate concentrations ($p < 0.01$), following the pattern observed in two wetland basins at the ORWRP (Mitsch and Nairn, 1995; Nairn and Mitsch, 1996). No significant differences were observed between the liner treatments in surface outflows.

3.4.4.7 Nitrate-Nitrogen

Nitrate concentrations were measured for outflows and leachate samples in both seasons (Figures 3.14 and 3.15). The reduction of nitrate in both outflow and leachate was significant ($p < 0.01$) and is the usual pattern observed in wetland treatment systems (Gersberg et al., 1985; Brodrick et al., 1988; Gumbright, 1992; Gale et al., 1993). Nitrogen removal occurs in part through the uptake of nitrogen in vegetation, but the majority of nitrogen removal often occurs through denitrification. Anaerobic sediments are the perfect habitat for various denitrifying bacteria to reduce nitrates and transform them into nitrogen gas (N_2), which is then lost to the atmosphere (Mitsch and Gosselink, 1993). Other losses from the nitrate pool may be through runoff and leaching (Cronk, 1992). Nitrate tends to leach through soil easily due to its negative charge. The nitrate concentration was almost zero in the leachate during the non-growing season. Denitrification seemed to be more stimulated by the development of a reduced soil environment. No differences between the liner treatments were observed in nitrate concentrations.

3.4.4.8 Mesocosm Plant Growth

Mean stem lengths in liner mesocosms were lower than those in no-liner mesocosms in both growing and non-growing season ($p < 0.01$) (Figure 3.16). Mean number of stems showed the same significant tendency during the growing season although the significant difference was marginal during non-growing season ($p = 0.056$) (Figure 3.17). Mean numbers of stems bearing flowers was lower in the liner mesocosms during the growing season ($p = 0.05$) (Figure 3.18). FGD by-products placed in the mesocosms showed a potential negative impact on plant growth, which was investigated further based on mesocosm productivity through plant harvesting in the 1998.

3.4.5 Summary of 1997 Observations

Summary statistics for all the parameters measured from the FGD mesocosm experiments in 1997 are presented in Table 3.2. FGD liner material placed with natural site soil was considered to be effective in removing phosphate in the leachate. Since the data for plant growth showed potential negative impact of FGD liner, phytotoxicity needed to be investigated based on productivity through harvesting and element analysis in the second year of study. Other chemical items measured in water samples showed no significant difference between the FGD liner and no liner treatments. The significantly higher pH of water samples in FGD liner mesocosms indicate that the FGD liner can be beneficial in treating acid mine drainage, which can be also added to treatment wetlands.

3.5 1998 Experiments

In 1998, the experiments begun in 1997 were continued but with plants now consisting of a much greater biomass than in the 1997 study. In the second-year study, we added phosphorus as super phosphate (P_2O_5, 46%) to one tank to provide high-P loading to 10 of the mesocosms, simulating the phosphorus concentration of treated wastewater going to a treatment wetland. Hence, the experimental design of the second-year study included four different treatment schemes such as liner plus riverwater (L+R), no-liner plus riverwater (N+R), liner plus P-spike water (L+P), and no-liner plus P-spiked water (N+P).

The second-year mesocosm tests were conducted from June 30, 1998 to September 13, 1998. Water levels and water flow were measured to maintain uniform hydrology in the 20 mesocosms with no differences between liner and no-liner treatments. Water level was checked three times a week during the experiment. The flow rate of riverwater into the mesocosms was measured with a graduated cylinder and a timer. Similar hydrology in liner and no-liner mesocosms was maintained. Comparison of hydrology among the treatments in the second-year experiments did not show any significant differences ($p = 0.52$ by flow rate, 900 mL/min) (Figure 3.19).

3.5.1 Field Sampling and Analysis Procedures

In general, the field sampling and water quality analyses procedures outlined in Section 3.4.3 were followed. Water sampling was done three times-per-week for four weeks. Surface outflow samples were collected directly from the mesocosm outlets and leachate was obtained from the standpipe connected to the bottom layer of the mesocosms. Two mesocosms which were not hydrologically sound in leachate collection due to the lack of leachate coming up in the standpipe were removed from the study. Therefore, only 18 mesocosms were included in the leachate analysis and all 20 mesocosms were included in the analysis of outflow.

Turbidity was determined on the day of sampling with a Hach Model 18900 Ratio Turbidimeter. Samples were analyzed later by a Lachat QuickChem IV Flow Injection Analysis (FIA) System.

All analyses for total phosphorus (APHA, 1992 4500-PF), orthophosphate (APHA, 1992 Method4500-PF) and NO2+NO3-N (APHA, 1992 4500-NO3E) were done on the Lachat autoanalyzer. All samples and standards were at room temperature and were vigorously mixed by inversion for analysis. Five prepared standards, a check standard and distilled water blank were run each time that an analysis was conducted. Standards were always within 10 % of the prescribed values.

Survey for the growth of wetland vegetation was similar to that employed for the 1997 experiments as elaborated in Section 3.4.2. Number of stems, number of stems bearing flowers and stem lengths were investigated weekly in each mesocosm during the second year experiment. For stem length, 20 randomly chosen stems were measured for each mesocosm with a ruler.

After two growing seasons, plant biomass harvesting was carried out at the end of second-year experiment (August 20 through September 13, 1998). All aboveground stems were cut at the soil surface. The plant samples were placed in plastic bags and weighed in the field with a hanging balance (accuracy to 40 g). Sub-samples were taken to a laboratory where both wet weight and dry weight were determined to estimate dry/wet ratios. Ratios were multiplied by total wet weight of the biomass from each mesocosm to estimate each dry weight production afterward. Sub-samples were allowed to dry until constant weight at 60°C, and some of them were ground to pass a 1 mm screen using Wiley Mill. Five grams of each sample kept in a paper coin envelope was sent for analysis of plant tissue elements by Inductively Coupled Plasma (ICP) emission spectrometry to Ohio Agricultural Research and Development Center's (OARDC's)

Star Laboratory in Wooster, Ohio. The samples included above- and below-ground biomass of the plants.

Soil samples were also taken after aboveground biomass harvesting from the approximately top 5 cm of the surface of the mesocosm soil surface to see if FGD material buried on the bottom of the mesocosms translocates into the upper layer of soil, which may have impacts on surface water quality of the wetlands. Three small samples were taken from each mesocosm and made into a composite sample to represent each mesocosm. Soil samples were air-dried and ground using a mortar and pestle to pass a 2 mm screen to sieve out stones. The samples prepared were sent to Star Laboratory at OARDC in Wooster, Ohio for analysis of the elements by ICP.

Data analyses were conducted as a two-way analysis of variance using the General Linear Model (GLM) procedure in SAS (SAS Institute, 1988) with FGD liner and phosphorus addition as main effects for all the items measured in water quality, plant morphometric measurements, plant biomass and element analysis. In case of plant morphometry and water quality data, averages of the parameters measured were calculated for each treatment for each sampling day and then used for statistical analysis. Orthophosphate concentration of leachate obtained below the detection limit was treated as 0. Thus, calculated concentrations represent minimum estimates. Duncan's multiple tests were used to test all pairwise contrasts of means for significance at $P < 0.05$ and LSD (least significant difference) test was also run for elemental analysis among the treatments to detect the difference, if any, more vigorously (Steel et al., 1997).

3.5.2 Results and Discussion

3.5.2.1 Conductivity

Conductivity data showed a significant difference in leachate conductivity between lined and unlined mesocosms ($p < 0.05$) (Figure 3.20). Liner treatment increased the conductivity of leachate significantly, which was also much higher than the values from previous year (Table 3.3). No difference between the treatments was observed for surface outflow.

3.5.2.2 pH

Generally, the pH of water samples was lower and more stabilized in the second year compared to the first-year (Table 3.3). It seems that the high pH caused by FGD liner treatment reduced over time for surface outflow, whereas the pH of leachate was still significantly higher ($p < 0.05$) in lined mesocosms than that of unlined mesocosms (Figure 3.21). No difference was observed between the two different phosphorus loadings.

3.5.2.3 Redox

The redox values in both outflow and leachate were much lower during the second-year experiment compared to the first year, reflecting much reduced conditions developed in soil over time (Table 3.3 and Figure 3.22). Most of the leachate redox values were below 100 mV, indicating it was reduced enough for ferric iron (Fe^{3+}) to be reduced into ferrous iron (Fe^{2+}). Iron reduction would influence phosphorus dynamics in the system because the inorganic phosphorus adsorbed with iron and aluminum oxyhydroxide can be released back to the water from sediments (Reddy and D'Angelo, 1994). In addition, nitrogen and manganese are known to be reduced fewer than 100mV of redox potential. The lowered redox is thought to have stimulated nitrate removal of the leachate through denitrification. Usually, nitrate becomes reduced and is lost into the atmosphere by denitirification when the redox potential is below 225 mV (Mitsch and Gosselink, 1993). The FGD liner treatment caused significant differences in redox potential ($p < 0.05$) of leachate showing much lower values in the mesocosms lined with FGD. FGD liner material consists of mostly $CaSO_3$ which is known to be very strong antioxidant that consumes available oxygen (Hao, 1998), which may have resulted in lower redox values in lined mesocosms. No difference was observed among the treatments in surface outflow.

3.5.2.4 Turbidity

Outflow and leachate samples were investigated for turbidity analysis (Figure 3.23). Turbidity decreased significantly from surface inflow to surface outflow in all 20 mesocosms ($p < 0.01$) during the experiment, showing the same tendency observed from the two experimental basins of ORWRP (Mitsch et al., 1998).

3.5.2.5 Orthophosphate

More than 80 % of orthophosphate input was removed from mesocosms fed by river water inflow, the same pattern as observed in the previous year's study (Table 3.3). There was no difference between the FGD liner treatment and the control in the orthophosphate concentration of surface outflow (Figure 3.24). The surface outflow from the mesocosms that had P-spiked inflow during the experiment also showed a decrease in the concentration. The FGD liner treatment showed much better performance in orthophosphate retention compared to no-liner treatment ($p < 0.05$). More effective Ca-P precipitation may have resulted from the addition of liner material since FGD liner contains more calcium in its composition than do natural clay soils (Ahn et al. 1998). All leachate showed significant reduction in phosphate concentrations ($p < 0.01$) compared to inflow concentrations. Especially, under the high-P loading, phosphate removal efficiency was 100 % whether or not they were lined with FGD. Most of the orthophosphate concentrations of leachate remained under the detection limit resulting in more than 90 % removal rate regardless of the treatments in the second year (Figure 3.24).

3.5.2.6 Total Phosphorus

Total phosphorus was more effectively removed from P-spiked surface water passing through wetland mesocosms lined with FGD by-product than through those with no FGD liner (Figure 3.25). The same tendency was observed in the mesocosms with river water inflow, but the difference in phosphorus removal between lined and unlined mesocosms was not significant. Compared to the pattern of the first year, the removal efficiency of total phosphorus from the mesocosms fed by river water dropped and the system seemed to start becoming a source of phosphorus rather than a sink in the second year. Interestingly, this tendency was also vivid in the leachate. The leachate samples from the mesocosm fed by river water showed tremendous increase in their concentration of total phosphorus compared to inflow (Table 3.3). It seems that the system was adding more phosphorus to the water while the water was passing through the soil plus FGD liner complex.

3.5.2.7 Nitrite, Nitrate, & Nitrogen

The reduction of nitrate from inflow to both outflow and leachate was significant ($p < 0.01$) (Table 3.3). Lower redox in the leachate (Figure 3.22) indicates that redox was low enough for nitrates to be reduced by denitrification because anaerobic sediments are the perfect habitat for various denitrifying bacteria. Uptake of nitrate by the plants also partially contributes to the removal of nitrogen out of water. No significant difference in nitrogen removal was observed in both outflow and leachate among the treatments (Figure 3.26).

3.5.2.8 Plant Morphometry

Wetland vegetation (*Schoenoplectus tabernaemontani*) for 1998 showed fewer stems and fewer stems bearing flowers in mesocosms using FGD by-product as liners (Table 3.4), which was also observed in 1997. However, average stem growth was not significantly different between the FGD lined and unlined mesocosms (Table 3.3) showing that the plants may have overcome the possible phytotoxicity or growth retardation which might have been caused by FGD by-product in the first-year.

3.5.2.9 Plant Biomass

There was no difference in biomass (belowground, aboveground, and total) of wetland plant between lined and unlined mesocosms in either river water or phosphorus-spiked inflows at the end of two years' experiments (Figure 3.27). Aboveground biomass showed slightly lower values in lined mesocosms compared to unlined mesocosms, but the difference was not significant ($p = 0.094$).

3.5.2.10 Plant Tissue Analysis

The ICP analysis for plant tissue material is summarized in the Table 3.5 according to the treatments. In the analysis of aboveground tissue, significantly higher concentration of Fe, Li, and lower concentration of Mo, Na were observed in the mesocosms lined with FGD ($p < 0.05$). There were several elements that showed significant difference in the tissue concentration of belowground biomass between liner treatments (Table 3.5). Al, B, Ba, Ca, Co, Cr, Fe, Li, Mg, S, Si, Sr, V, and Zn were increased significantly in the plants grown on the mesocosms lined with FGD ($p < 0.05$). Above and belowground biomass indicated that these major and trace elements supplied by the addition of FGD liner did not exert any significantly negative impact on the production of biomass (Figure 3.27).

Boron, which was concerned as an element causing phytotoxicity at high dosage although an element essential for plant growth (Aitken and Bell, 1985; Pierzynski et al., 1994; McLeod and Ciravolo, 1997; Mcleod and Ciravolo, 1998), was not different in the aboveground tissue of the plants in both lined and unlined wetlands. However, boron content in belowground tissue was significantly higher in the lined mesocosms compared to unlined mesocosms ($p < 0.05$). The higher tissue content of boron in the belowground from liner mesocosms did not seem to affect negatively on the biomass because there was no difference in the aboveground biomass ($p = 0.094$) as well as in the belowground biomass ($p = 0.68$) of the plants between lined mesocosms and unlined mesocosms. Boron can be phytotoxic to some plants (Nable et al., 1997) and can cause serious problems to these plants grown on soils irrigated with high-boron water (Gupta et al., 1985), some saline soils (Sankary, 1985), and plants growing on some pulverized fly ashes (El-Mogazi et al., 1988). Boron toxicity has been well-studied in agricultural crops and fruit trees, but research on wetland plants is rare (Sposito, 1988). McLeod and Ciravolo (1998) recently tested bottomland tree seedlings for boron tolerance and potential boron removal.

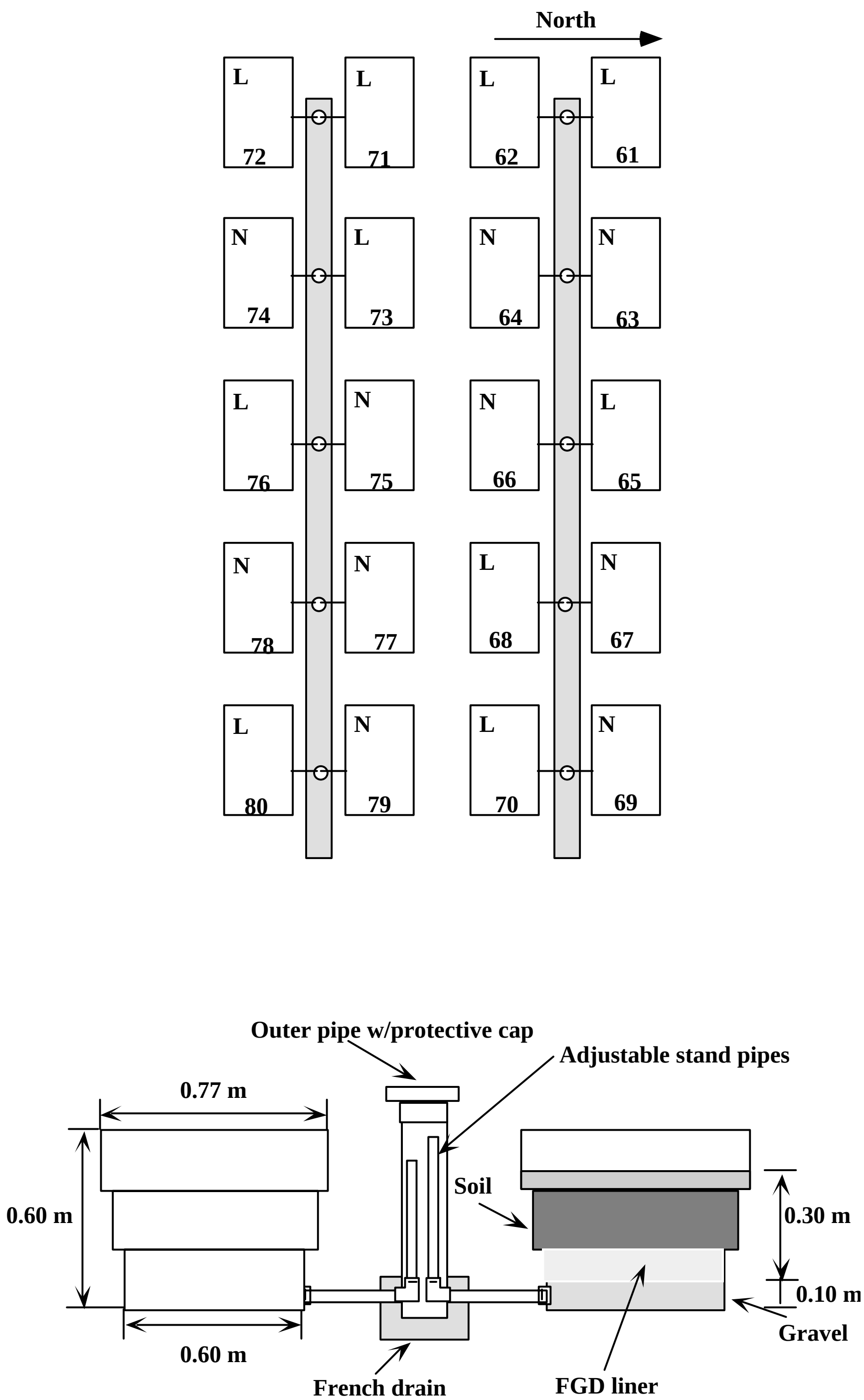
3.5.2.11 Surface Soil Analysis

The elemental analysis of surface soil is summarized in Table 3.6. Al, Ca, and Ni showed significant treatment effect of liner ($p < 0.05$). Soil Ca was higher in the lined mesocosms, whereas the Al and Ni were lower in the lined mesocosms. Higher Ca content of the surface soil in the lined treatment seemed to contribute to the immobilization of phosphorus lowering the phosphorus concentration of outflow water through the increased Ca-P precipitation (Figure 3.25). Low Al concentration in the soil may be attributed mainly to leaching and partially to plant uptake since there was significantly higher content of Al in the tissues of plants grown ($p = 0.005$) in the lined. Wendell and Ritchey (1996) found that high-calcium FGD by-products reduced aluminum toxicity in soil through decreased Al solubility due to increased pH (Hsu,

1977) and precipitation of soil Al-sulfates, which could be a contributing factor to the lower concentration of Al in the surface soil, if the precipitation occurred in the bottom layer of soil near the FGD liner. Soil amendment with $CaSO_4$ or $CaSO_3$ FGD by-products reduced Al toxicity and overcame Ca deficiency in their investigation. In our study, Ni was also higher in the tissue of plant grown in the FGD lined mesocosms, but the difference was not significant ($p = 0.093$). Some other mechanisms such as leaching may have contributed to the decreased concentration of this element in the soil. In the mesocosms with high-P inflow, the phosphorus concentration of the surface soil was significantly higher as expected. Vanadium (V) concentrations were also higher in high–P mesocosms relative to the low-P loading mesocosms.

3.5.3 Summary of 1998 Observations

The FGD mesocosm experiments for the second year showed that stabilized FGD by-product can be used in constructed wetlands as a liner. The small mesocosm studies indicated increased orthophosphate retention by the FGD lined mesocosms compared to the controls for phosphorous spiked inflow experiments. Total phosphorous was more effectively removed from phosphorous spiked surface water passing through FGD lined wetland mesocosms than controls. No difference in biomass of wetland plant between FGD lined and unlined mesocosms was observed although lower average stem length and fewer stems bearing flowers were observed in mesocosms with FGD material as liner. A larger-scale, long-term wetland experiment close to full-scale is suggested to better predict what would happen if FGD liner material were used on full-scale wetland basins in real situation.



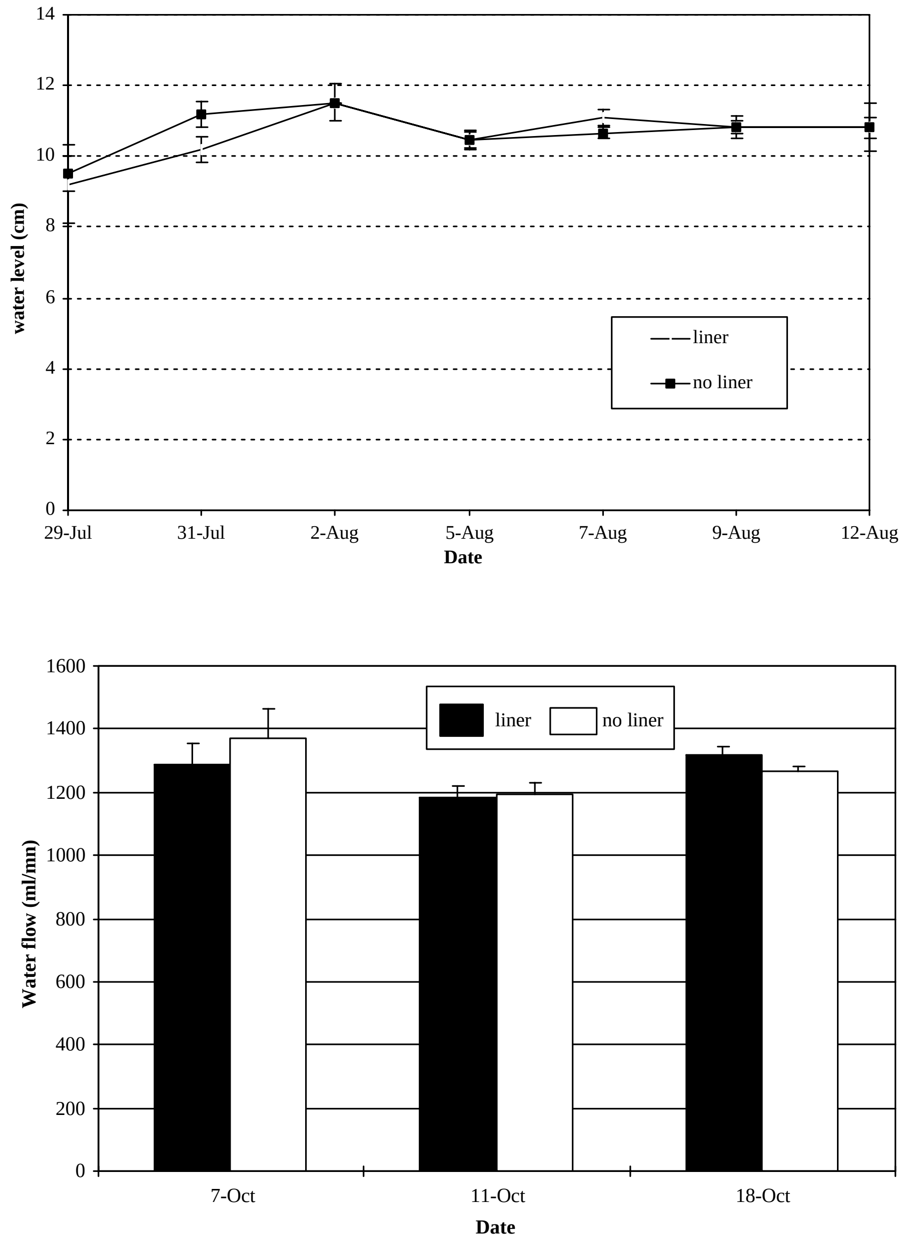
Mesocosms are identified by numbers and by the existence of liner material (L =liner, N= No liner)

Figure 3.1 Plan Diagram of 20 Mesocosms and French Drain System

Table 3.1 Estimated Chemical Composition (%) of FGD By-Product

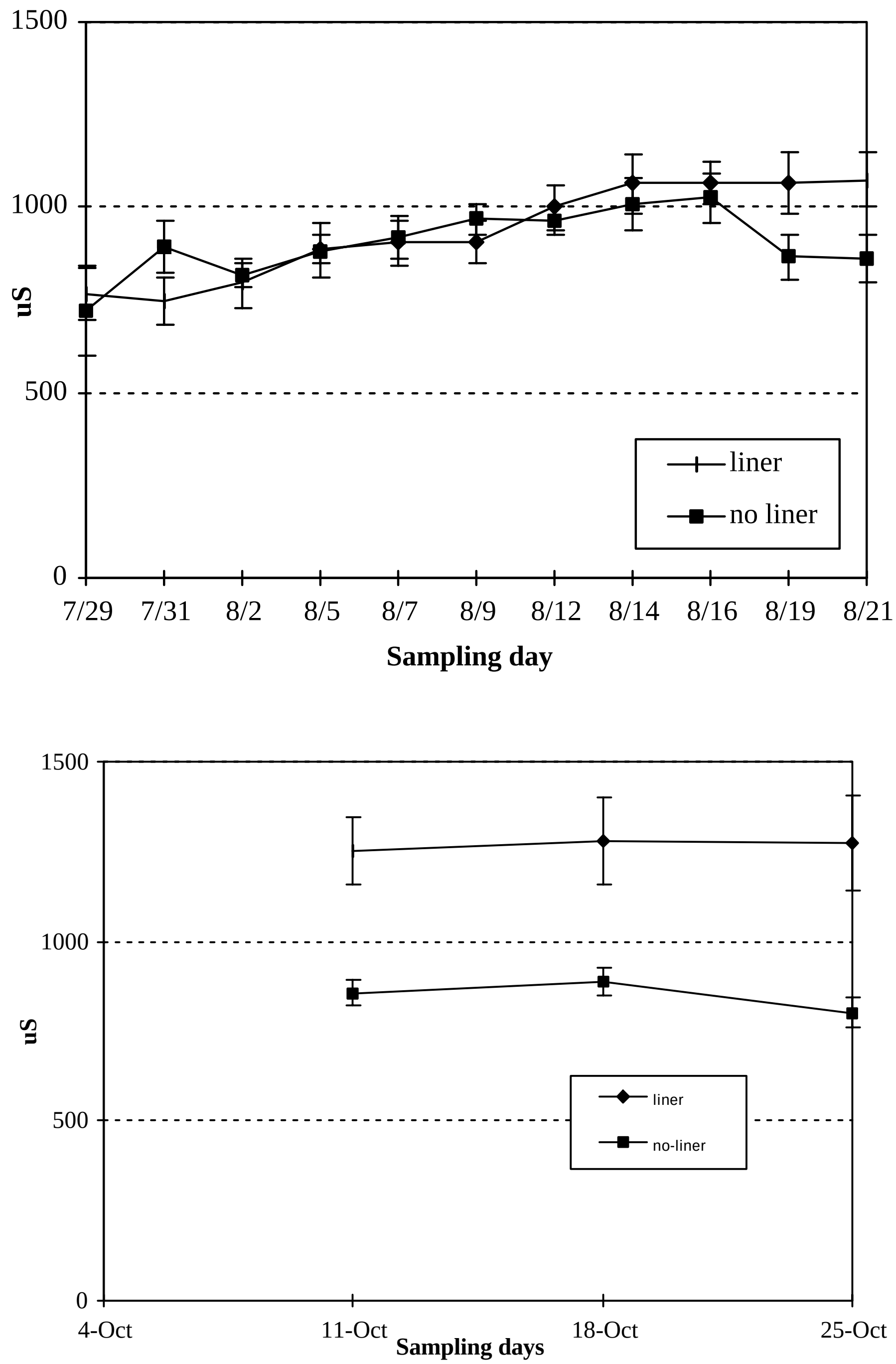
Moisture Content (105 ^{o}C)	23.78%
Calcium Oxide as CaO	21.55%
Magnesium Oxide as MgO	1.51%
Silicon Oxide as SiO_2	26.2%
Iron Oxide as Fe_2O_3	12.07%
Alumina as Al_2O_3	10.94%
Total Sulfur as S	5.97%
Sulfate as SO_3	1.67%
Sulfite as SO_2	10.58%
CO_2	4.24%
Loss on ignition (1100 °C)	12.85%

Figure 3.2 Photograph of FGD Liner Mesocosm Experimental Layout



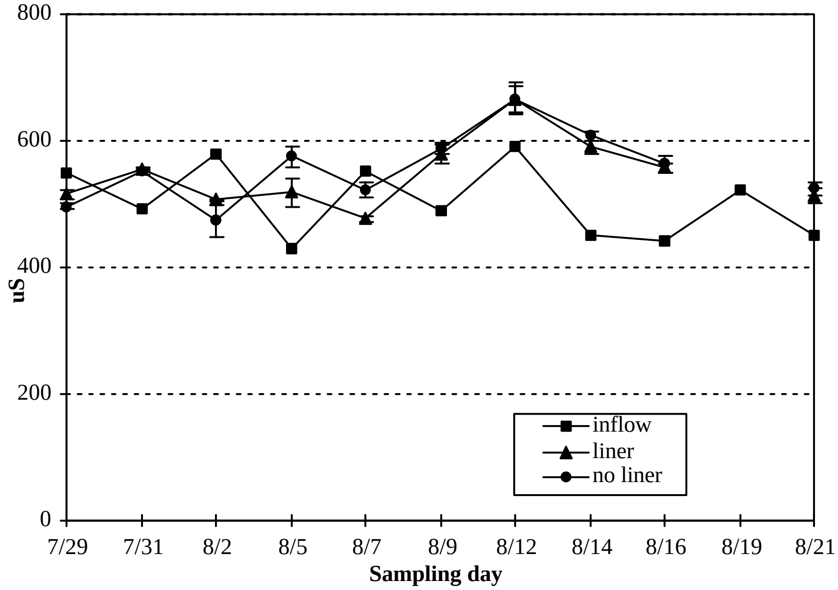
Note: Bars indicate standard errors

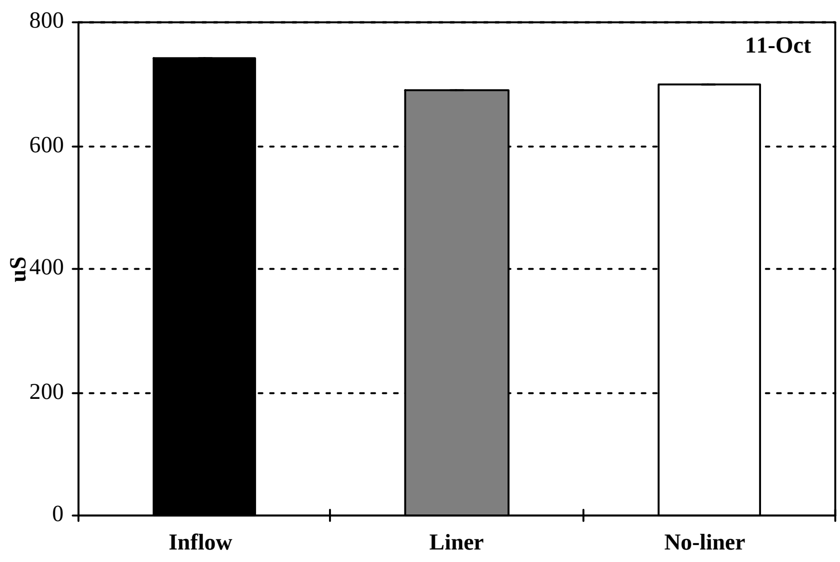
Figure 3.3 Mesocosm Hydrology During a) Growing and b) Non-Growing Season in 1997



Note: Bars indicate standard errors

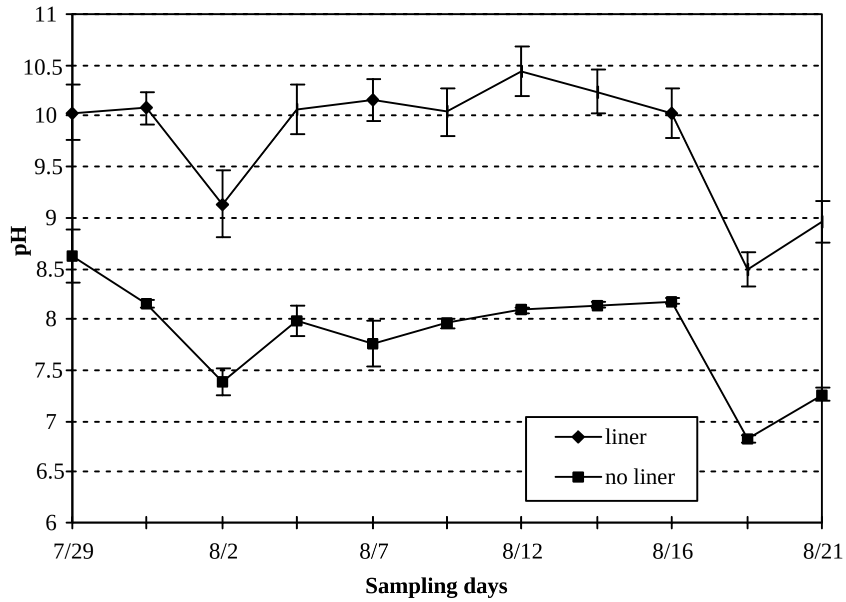
Figure 3.4 Conductivity of Leachate in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

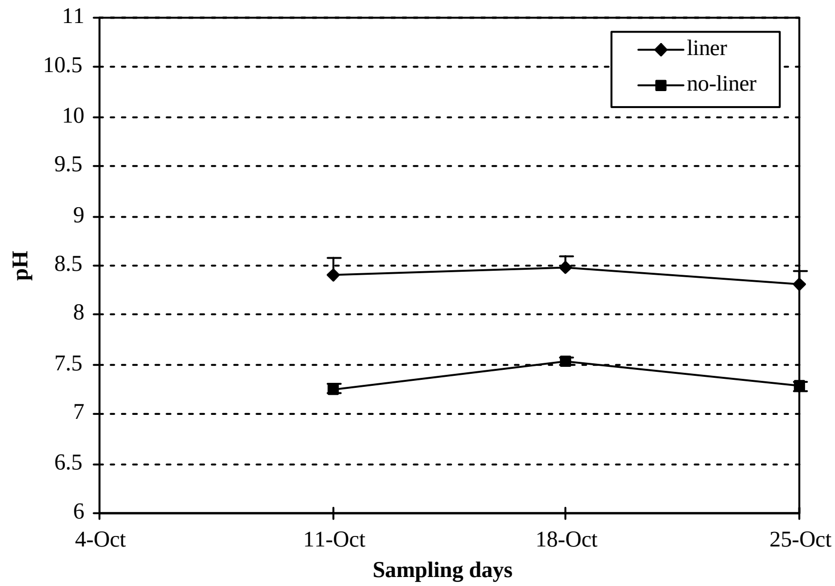




Note: Bars indicate standard errors

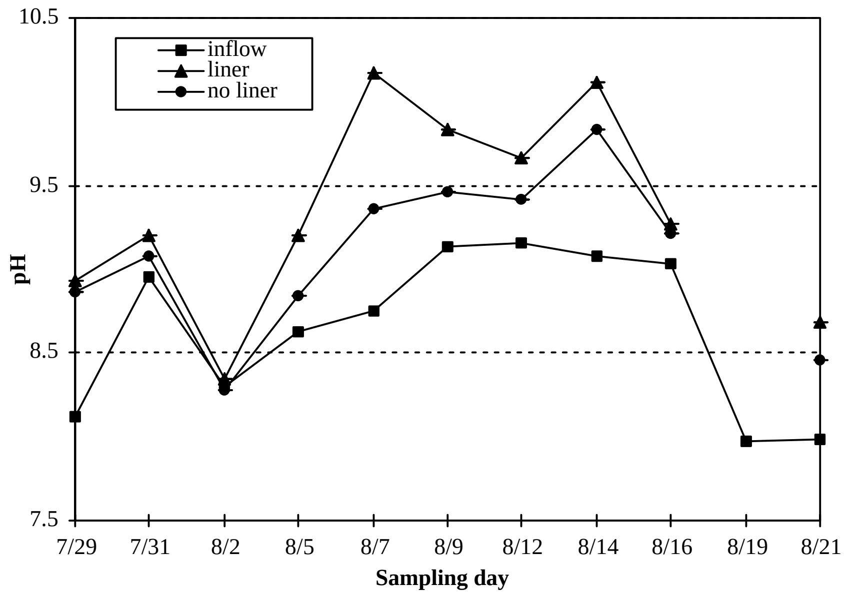
Figure 3.5 Conductivity of Surface Outflow in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

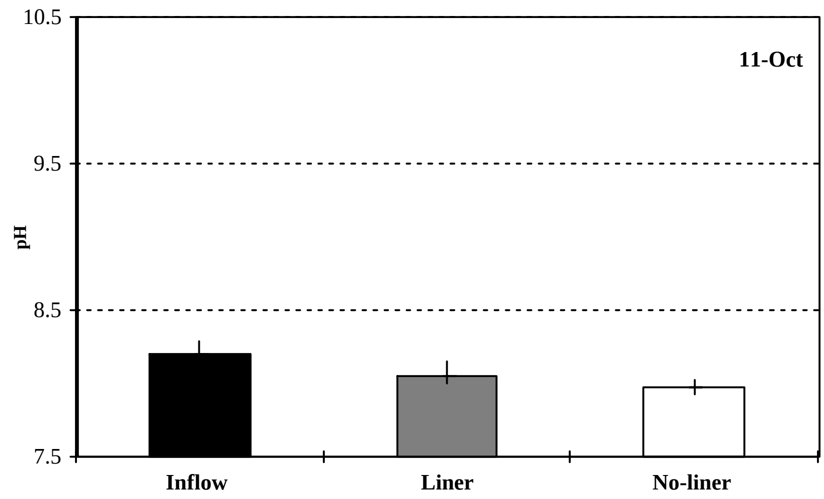




Note: Bars indicate standard errors

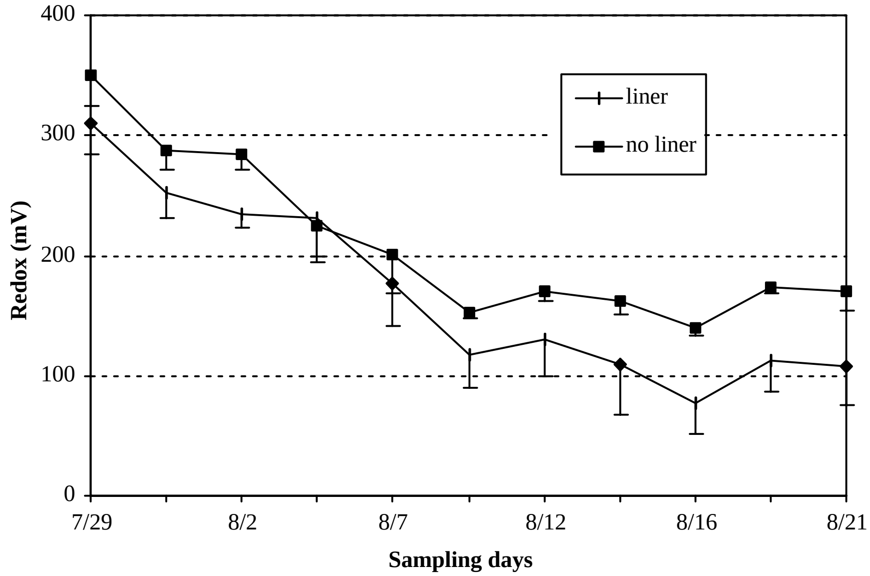
Figure 3.6 pH of Leachate in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

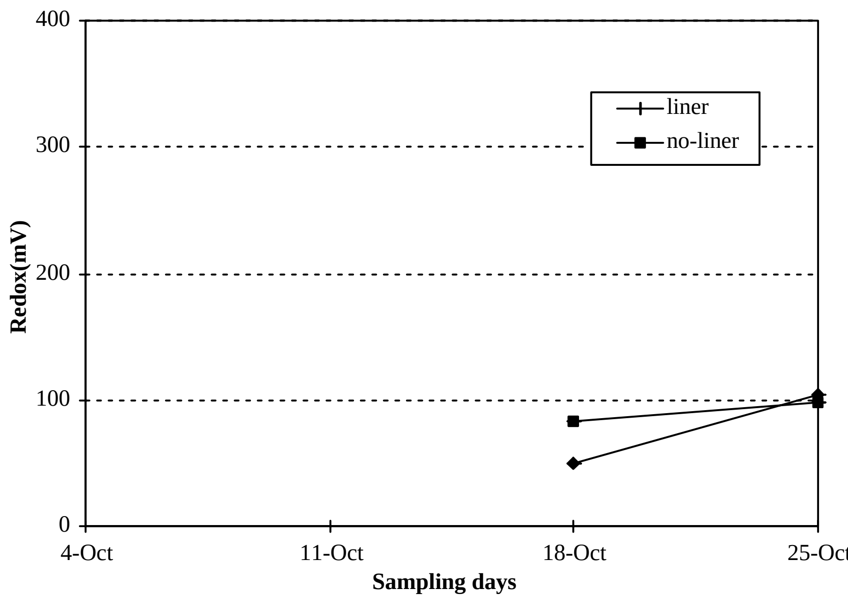




Note: Bars indicate standard errors

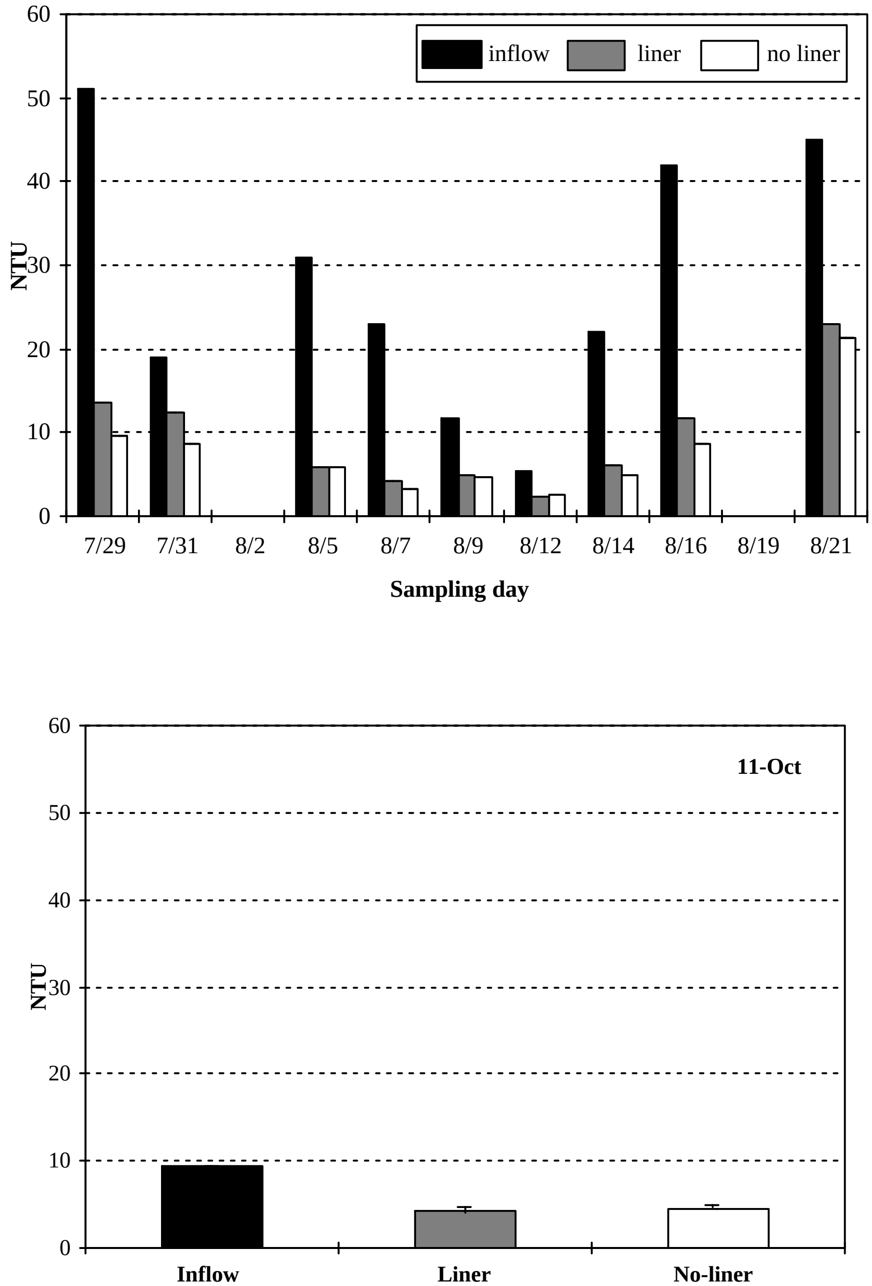
Figure 3.7 pH of Surface Outflow in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997





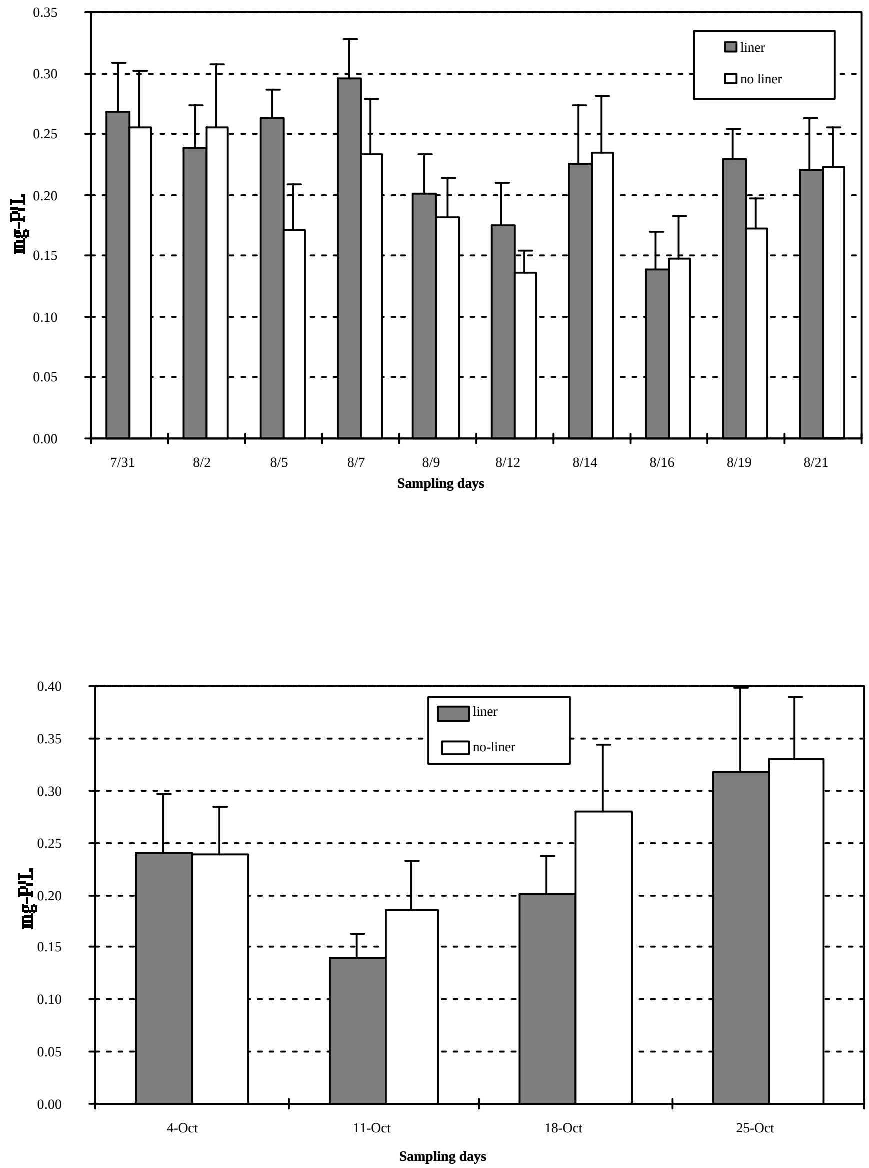
Note: Bars indicate standard errors

Figure 3.8 Redox in Leachate in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997



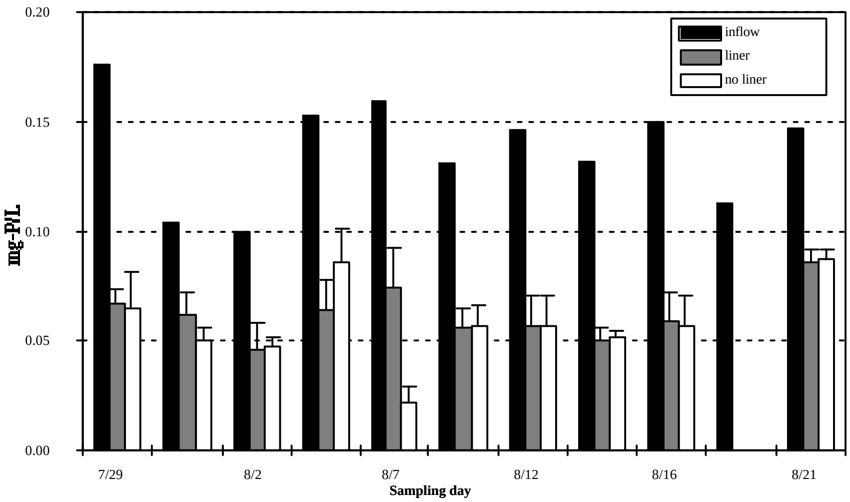
Note: Bars indicate standard errors

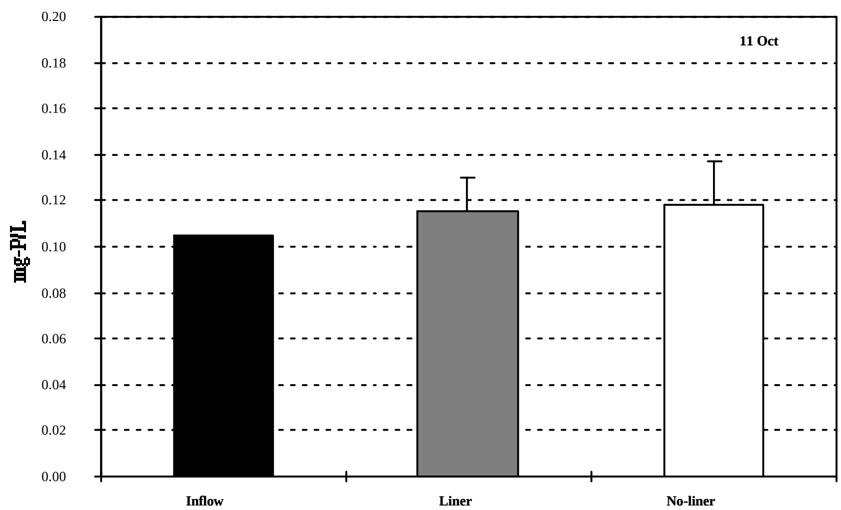
Figure 3.9 Turbidity of Surface Outflow in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997



Note: Bars indicate standard errors

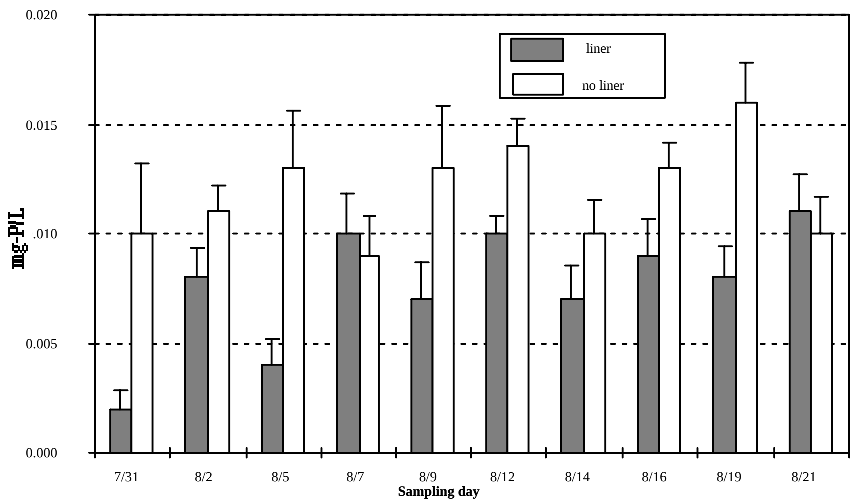
Figure 3.10 Total Phosphorous of Leachate in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

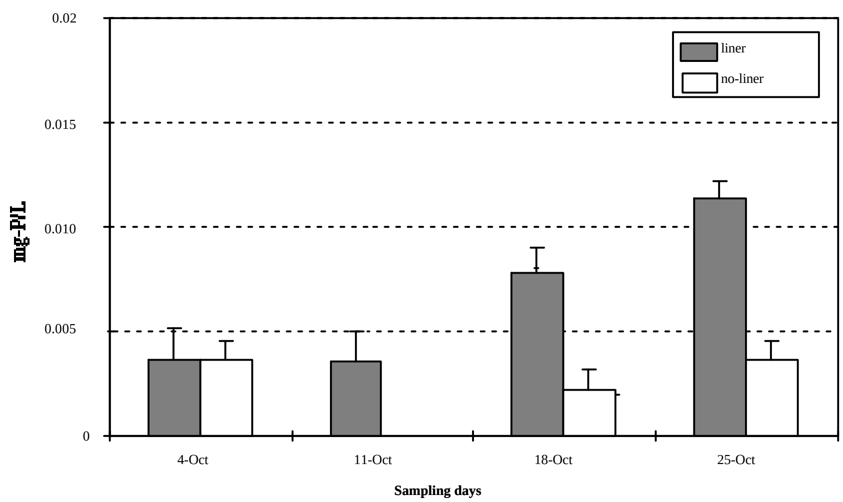




Note: Bars indicate standard errors

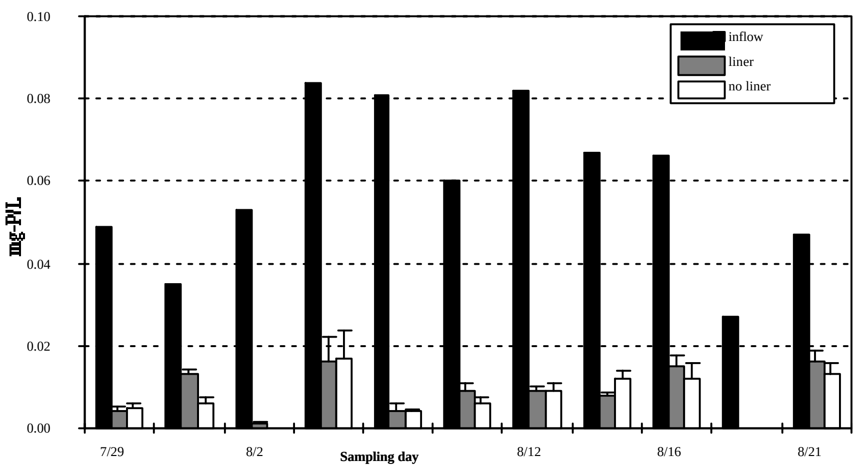
Figure 3.11 Total Phosphorous of Surface Outflow in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

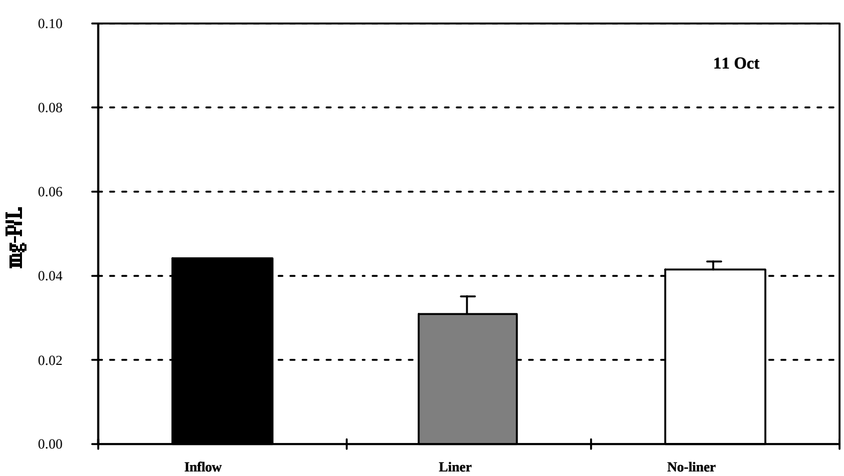




Note: Bars indicate standard errors

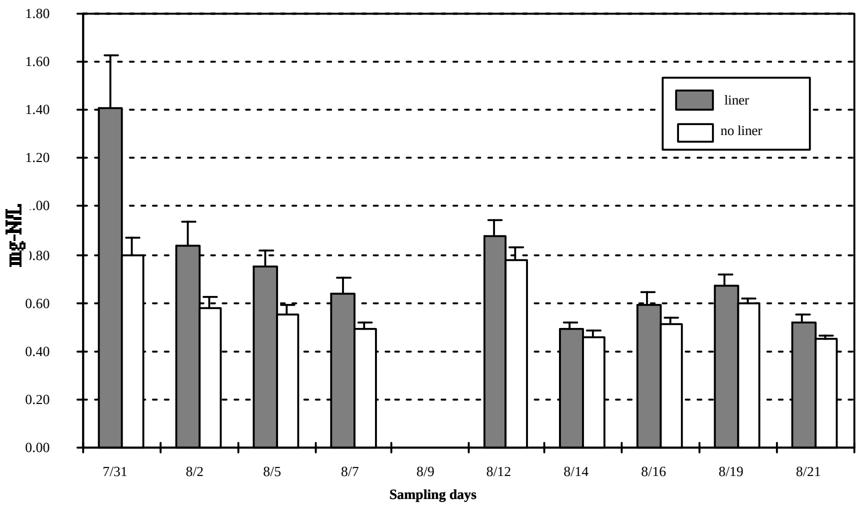
Figure 3.12 Orthophosphate of Leachate in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

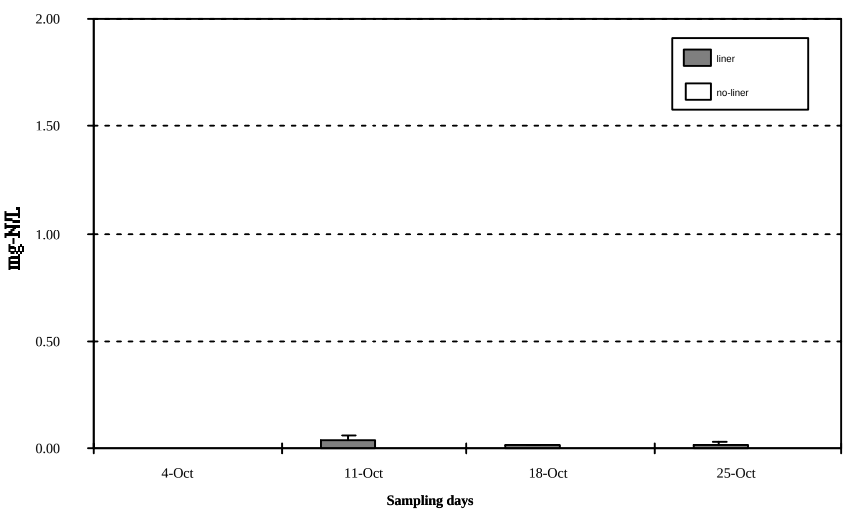




Note: Bars indicate standard errors

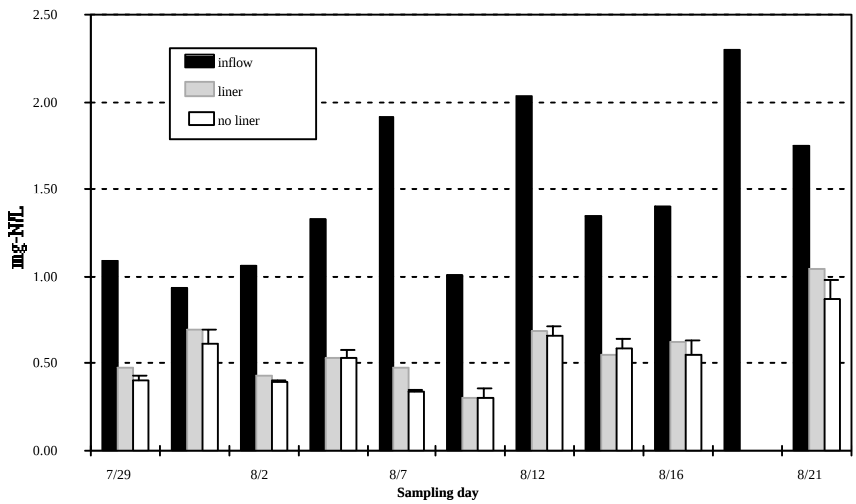
Figure 3.13 Orthophosphate of Surface Outflow in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

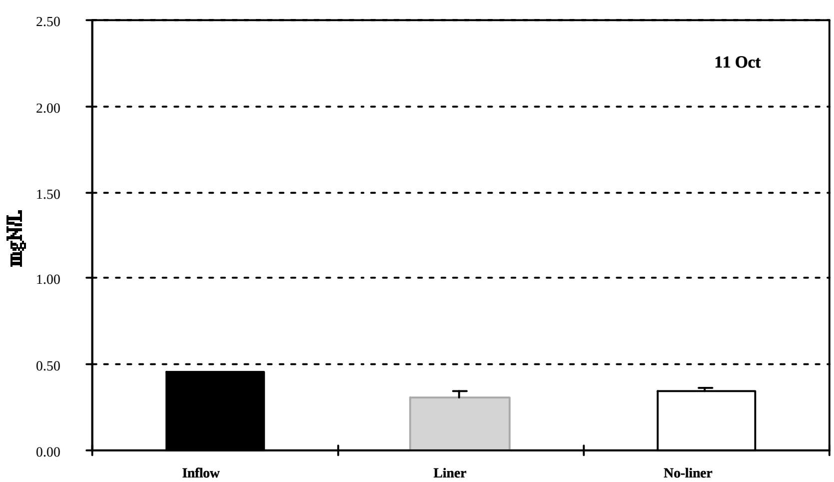




Note: Bars indicate standard errors

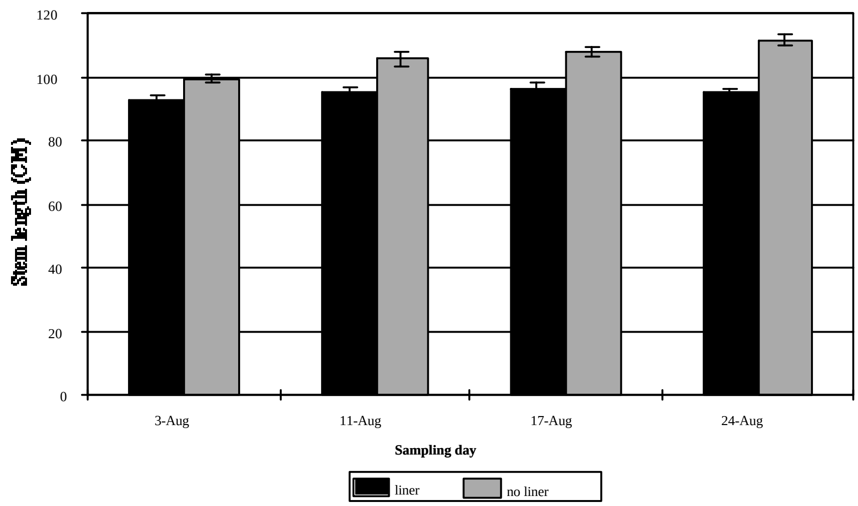
Figure 3.14 Nitrate in Leachate in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

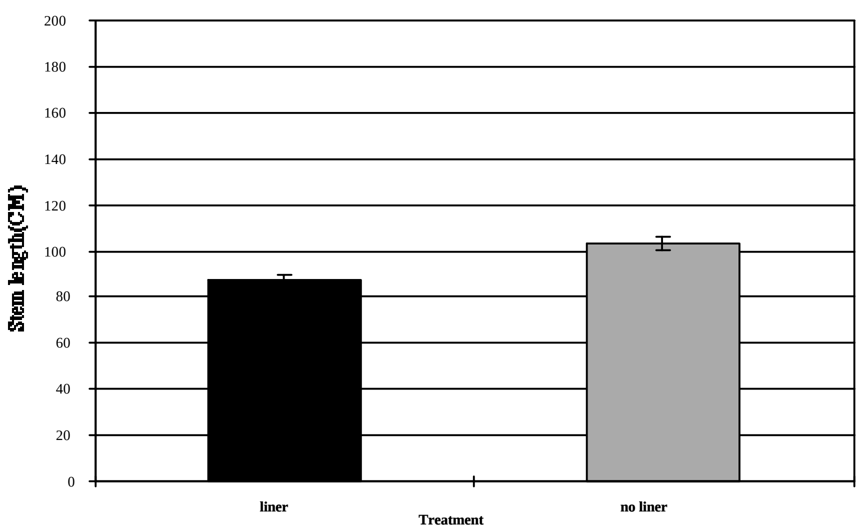




Note: Bars indicate standard errors

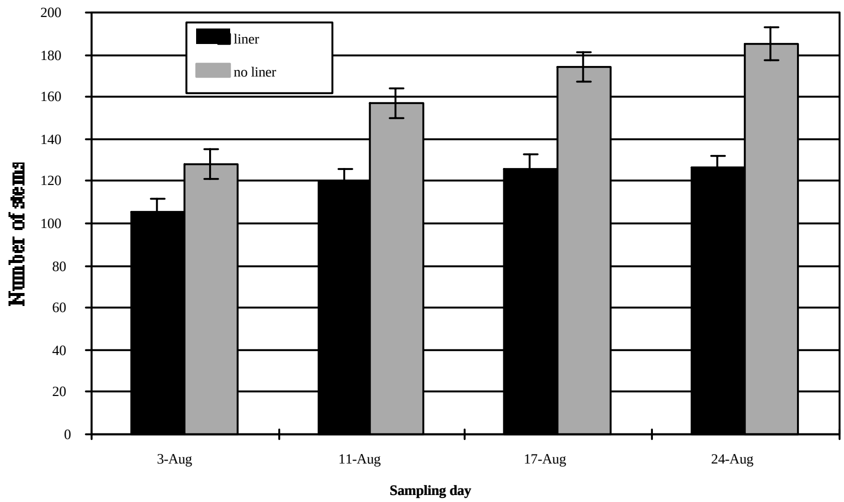
Figure 3.15 Nitrate in Surface Outflow in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

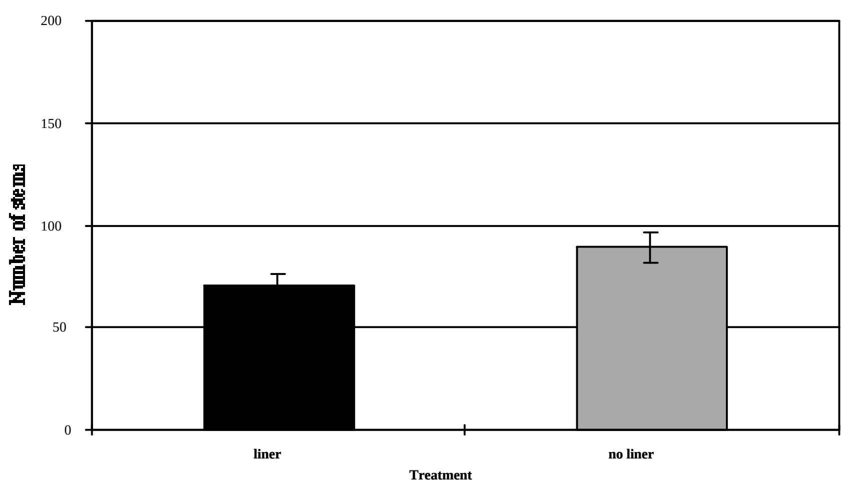




Note: Bars indicate standard errors

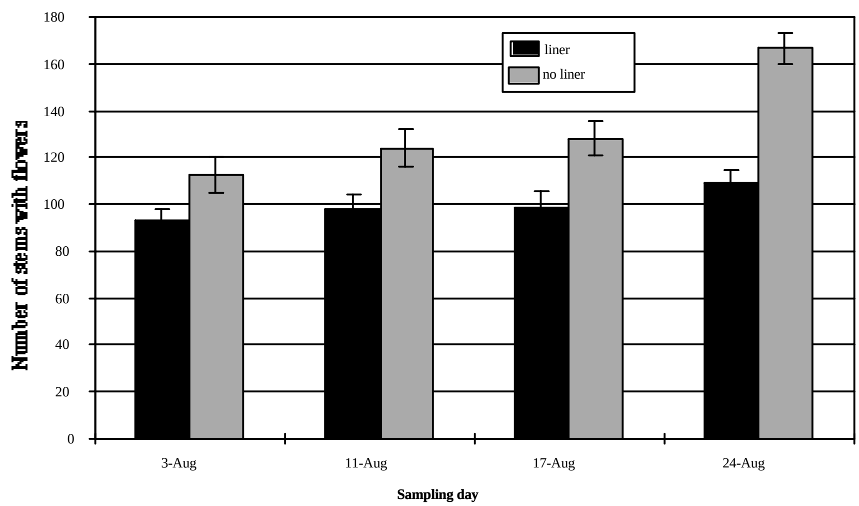
Figure 3.16 Stem Length of *S. Tabernaemontani* in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997





Note: Bars indicate standard errors

Figure 3.17 Number of Stems of *S. Tabernaemontani* in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997



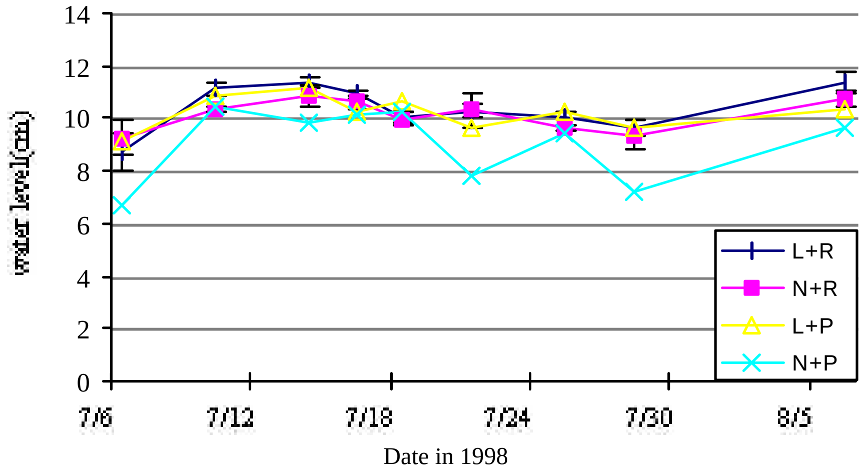
Note: Bars indicate standard errors

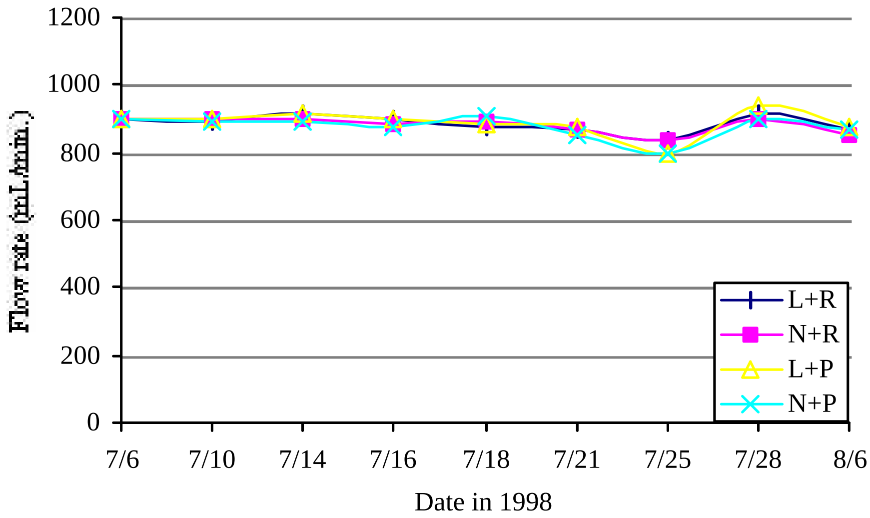
Figure 3.18 Number of Stems of *S. Tabernaemontani* with Flowers in Liner vs. No-Liner Mesocosms During a) Growing Season and b) Non-Growing Season in 1997

Table 3. 2 Statistical Comparison of Water Quality and Plant Growth in 1997

	Growing season (July-August)	Non-growing season(October)
Leachate		
DO (mg/L)	NS	NS
Cond.(µS)	NS	L > N**
pH	L > N**	L > N**
Redox (mV)	NS	NS
Total-P (mg-P/L)	NS	NS
Ortho-P (mg-P/L)	L > N**	NS
NO3-N (mg-N/L)	NS	NS
Outflow		
DO (mg/L)	NS	
Cond. (µS)	NS	Not available for statistical treatment due to the lack of data
pH	NS	
Redox (mV)	NS	
Turbidity (NTU)	NS	
Total-P (mg-P/L)	NS	
Ortho-P (mg-P/L)	NS	
NO3-N (mg-N/L)	NS	
Plant growth		
Number of stems	L < N**	L < N (p=0.056)
Number of stems w/flower	L < N**	
Stem length (CM)	L < N**	L < N**

L: Liner N: No liner
 * significant at the 0.05 level
** significant at the 0.01 level

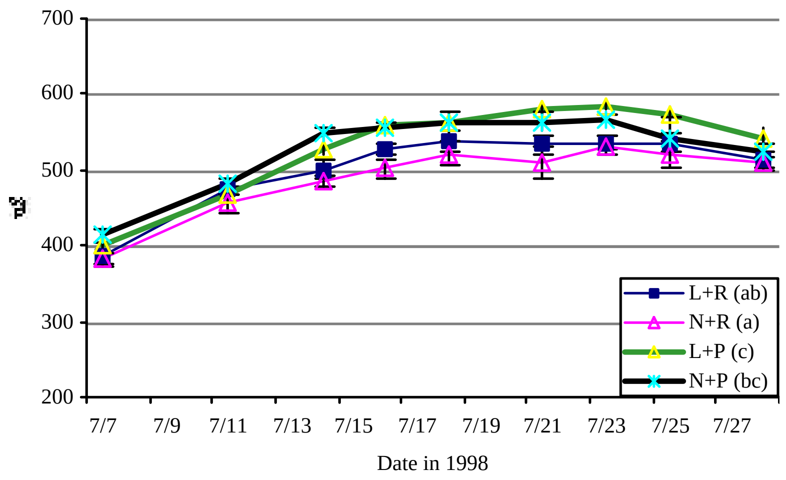




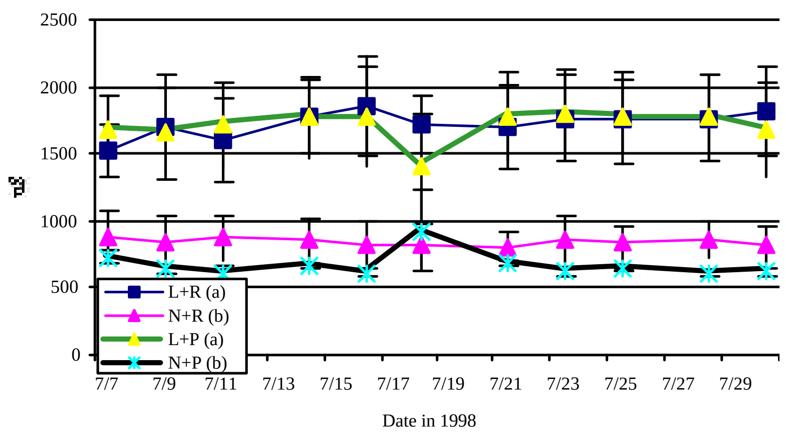
L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

Note: Bars indicate standard errors

Figure 3.19 Mesocosm Hydrology (Water Level and Flow Rate) in 1998



Surface Outflow



Leachate

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

Notes: 1. Bars indicate standard errors

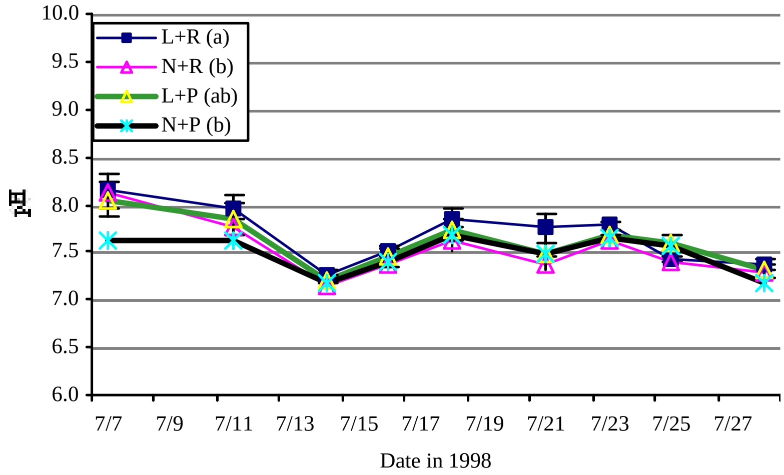
2. The same letters among the treatments indicates no statistical difference

Figure 3.20 Conductivity of Surface Outflow and Leachate in Liner vs. No-Liner Mesocosms in 1998

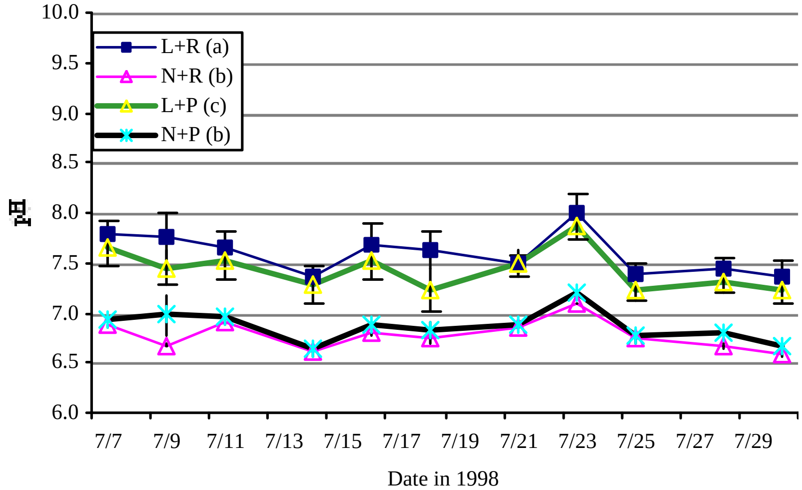
Table 3.3 Water Quality and Nutrient Measurements and Changes for FGD Mesocosms, 1997-1998 [a]

Year and parameter	Inflow	Surface outlfow liner	Surface outlfow no-liner	Percentage change, inflow to outflow liner	Percentage change, inflow to outflow no-liner	t-test [b]	leachate liner	leachate no-liner	Percentage change inflow to leachate liner	Percentage change inflow to leachate no-liner	t-test [b]
First year (1997)											
riverwater											
Temperature, °C	23.92	22.67	22.40	-4.7	-5.8	NS	23.93	23.51	+0.8	-1.0	NS
Turbidity, NTU [c]	27.8	9.4	7.7	-64.2	-69.5	NS					
Dissolved Oxygen, mg/L	6.19	7.11	6.20	+26.8	+10.3	NS	0.44	0.33	-92.8	-94.4	NS
pH	8.72	9.34	9.08	+7.2	+4.2	NS	9.79	7.85	+13.9	+8.6	*
Conductivity, uS/cm	503	548	557	+10.24	+12.32	NS	934	902	+86.8	+83.3	NS
Redox potential, mV	448	409	415	-8.5	-7.0	NS	169	211	-60.1	-51.3	NS
Orthophosphate, mg/L	0.062	0.010	0.008	-83.4	-86.3	NS	0.008	0.012	-87.9	-81.0	*
Total Phosphorus, mg/L	0.140	0.062	0.065	-55	-53.7	NS	0.226	0.201	+71.2	+57.6	NS
Nitrate, mg/L	1.39	0.58	0.52	-56.7	-60.8	NS	0.75	0.58	-41.0	-57.2	NS
Second year (1998)											
riverwater											
Temperature, °C	25.01	24.09	23.83	-3.5	-4.5	NS	23.75	23.19	-4.6	-7.0	NS
Turbidity, NTU	11.66	5.88	5.39	-41.1	-44.9	NS					
Dissolved Oxygen, mg/L	4.90	2.40	2.14	-50.1	-56.4	NS	0.57	0.54	-88.3	-88.8	
pH	7.41	7.67	7.52	+3.6	+1.5	*	7.60	6.81	+2.7	-8.0	*
Conductivity, uS/cm	513.11	505.16	490.90	-2.1	-5	NS	1719.7	847.8	+244.6	+71.9	*
Redox potential, mV	340.89	199.50	201.13	-40.4	-39.9	NS	-10.3	61.3	-104.4	-82.2	*
Orthophosphate, mg/L	0.057	0.011	0.011	-80.9	-81.3	NS	0.002	0.001	-94.9	-97.1	*
Total Phosphorus, mg/L	0.126	0.116	0.157	-5.7	+30.1	NS	0.840	0.717	+584.6	+518.2	NS
Nitrate plus nitrite, mg/L	1.96	0.89	0.74	-47.9	-59.8	NS	0.25	0.23	-83.1	-85.2	NS
P-spiked water											
Temperature, °C	25.56	24.23	24.13	-5.1	-5.5	NS	23.76	23.55	-6.8	-7.6	NS
Turbidity, NTU	17.44	5.36	6.44	-61.3	-54.3	NS					
Dissolved Oxygen, mg/L	4.79	2.99	2.30	-37.1	-51.0		0.60	0.30	-86.8	-93.4	
pH	7.25	7.59	7.48	+4.7	+3.3	NS	7.46	6.88	+2.8	-5.1	*
Conductivity, uS/cm	519.78	533.17	529.13	+1.8	+1.6	NS	1719.9	676.7	+242.1	+34	*
Redox potential, mV	345.56	227.80	230.85	-32.6	-31.1	NS	19.4	42.7	-95.0	-87.8	NS
Orthophosphate, mg/L	2.169	1.082	1.506	-49.1	-29	*	0.000	0.000	-99.9	-100	NS
Total Phosphorus, mg/L	2.850	1.472	2.032	-48.6	-28.6	*	0.313	0.324	-89.6	-88.7	NS
Nitrate plus nitrite, mg/L	2.11	0.66	0.88	-63.2	-54.6	NS	0.27	0.33	-84.2	-79.6	NS

[a] Numbers shown in the table are presented as average of all data collected during the experiment period.
[b] liner versus no-liner; NS, no significant difference at a = 0.05; * significant difference at a = 0.05
[c] NTU, Nephelometric Turbidity Units.



Surface Outflow



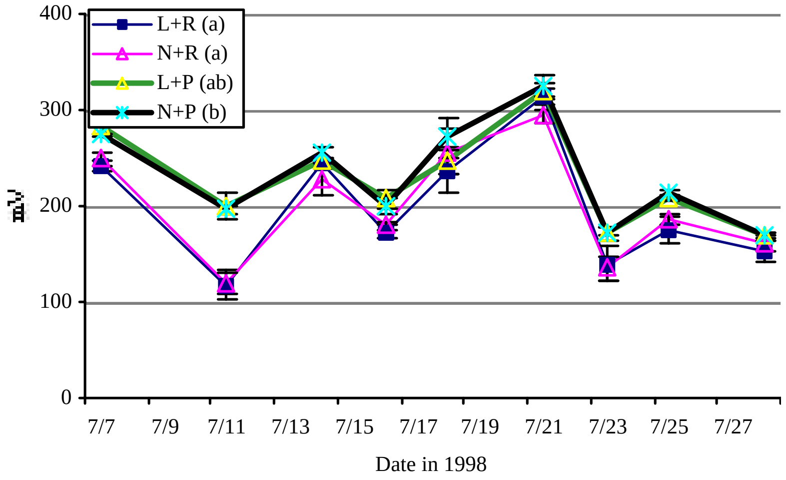
Leachate

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

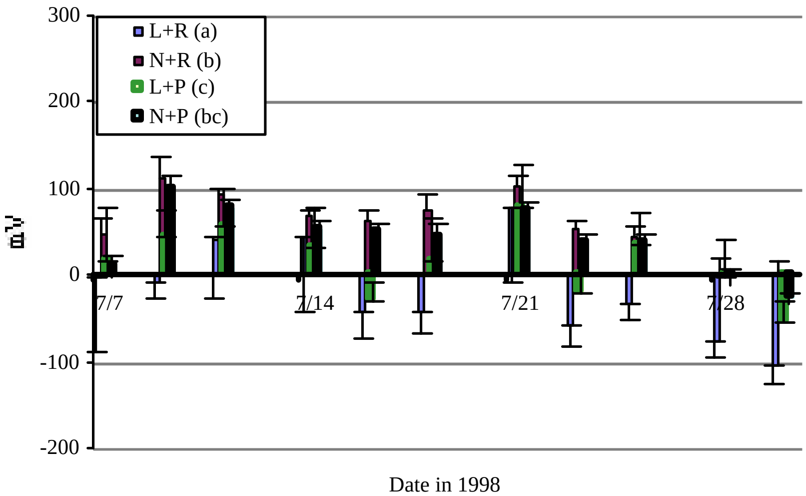
Notes: 1. Bars indicate standard errors

2. The same letters among the treatments indicates no statistical difference

Figure 3.21 pH of Surface Outflow and Leachate in Liner vs. No-Liner Mesocosms in 1998



Surface Outflow



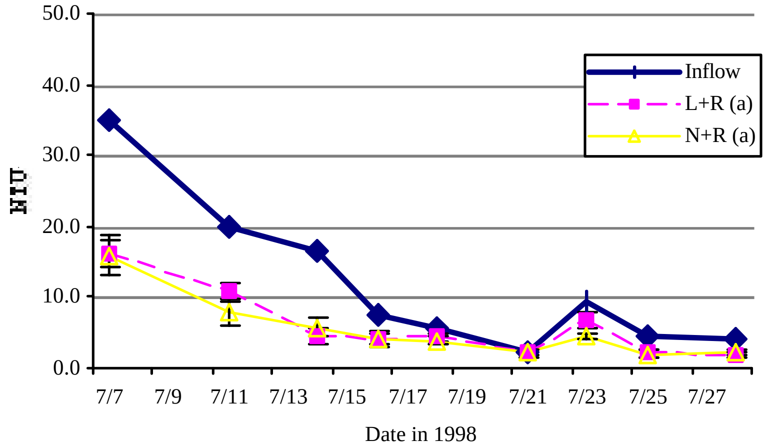
Leachate

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

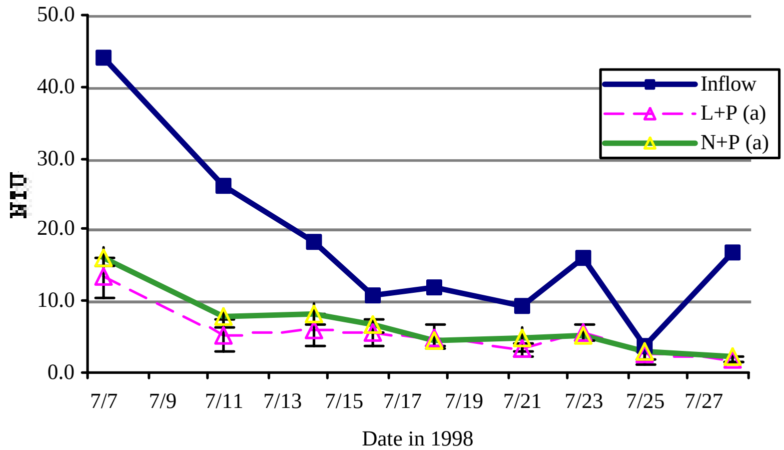
Notes: 1. Bars indicate standard errors

2. The same letters among the treatments indicates no statistical difference

Figure 3.22 Redox of Surface Outflow and Leachate in Liner vs. No-Liner Mesocosms in 1998



Surface Outflow



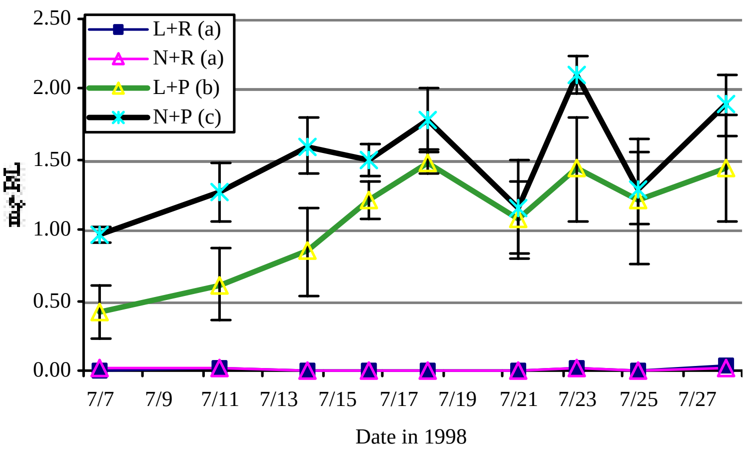
Leachate

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

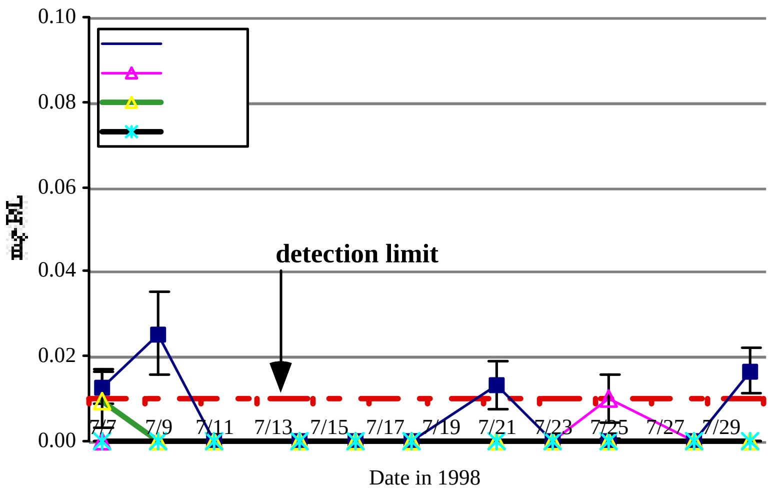
Notes: 1. Bars indicate standard errors

2. The same letters among the treatments indicates no statistical difference

Figure 3.23 Turbidity of Surface Outflow and Leachate in Liner vs. No-Liner Mesocosms in 1998



Surface Outflow



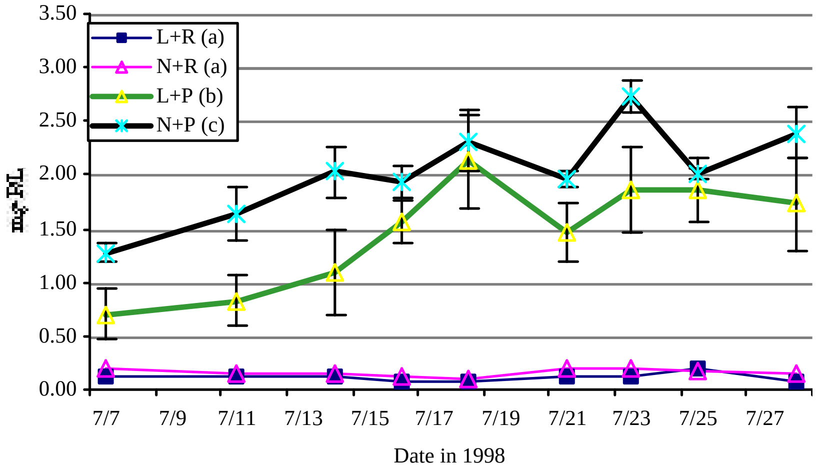
Leachate

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

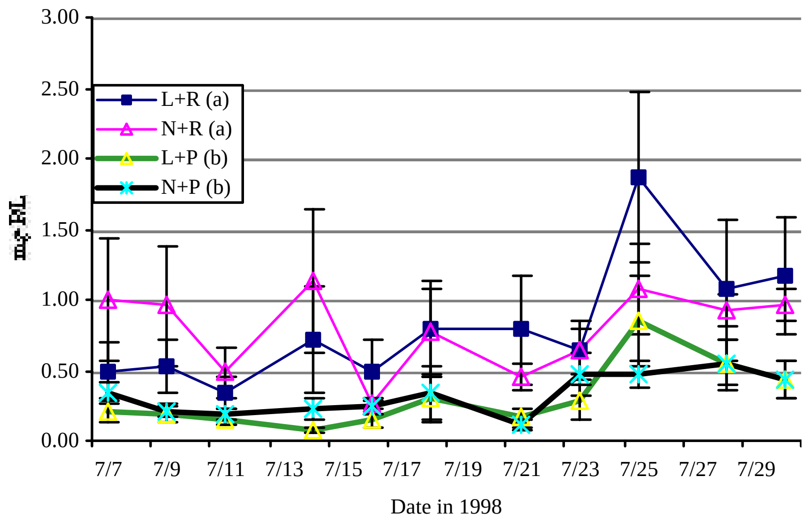
Notes: 1. Bars indicate standard errors

2. The same letters among the treatments indicates no statistical difference

Figure 3.24 Orthophosphate of Surface Outflow and Leachate in Liner vs. No-Liner Mesocosms in 1998



Surface Outflow



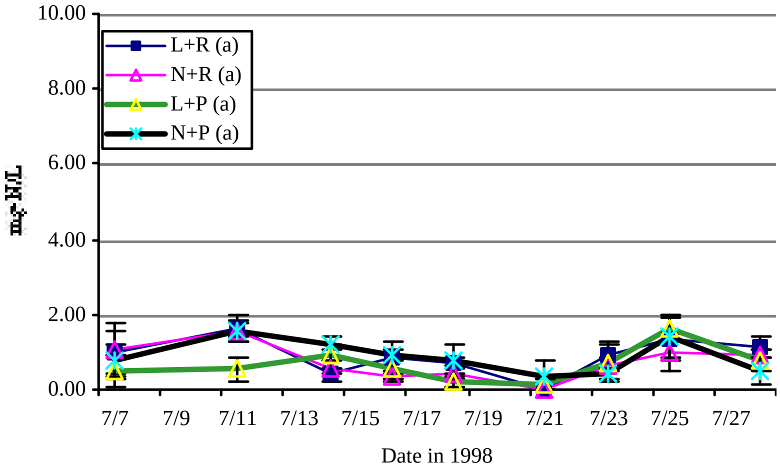
Leachate

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

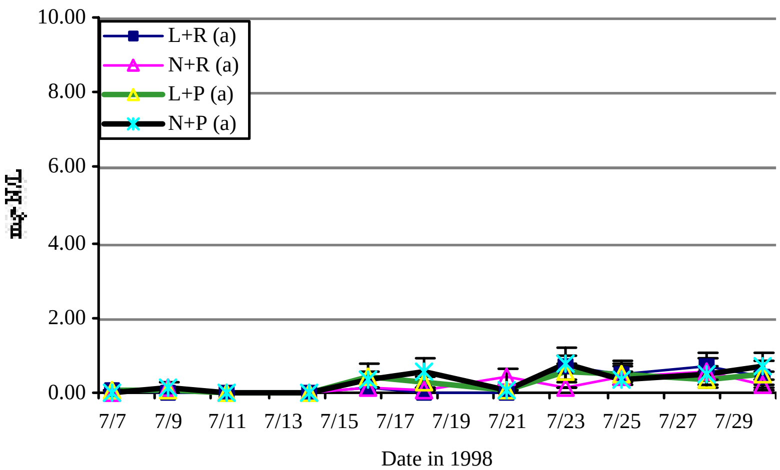
Notes: 1. Bars indicate standard errors

2. The same letters among the treatments indicates no statistical difference

Figure 3.25 Total Phosphorous of Surface Outflow and Leachate in Liner vs. No-Liner Mesocosms in 1998



Surface Outflow



Leachate

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

Notes: 1. Bars indicate standard errors

2. The same letters among the treatments indicates no statistical difference

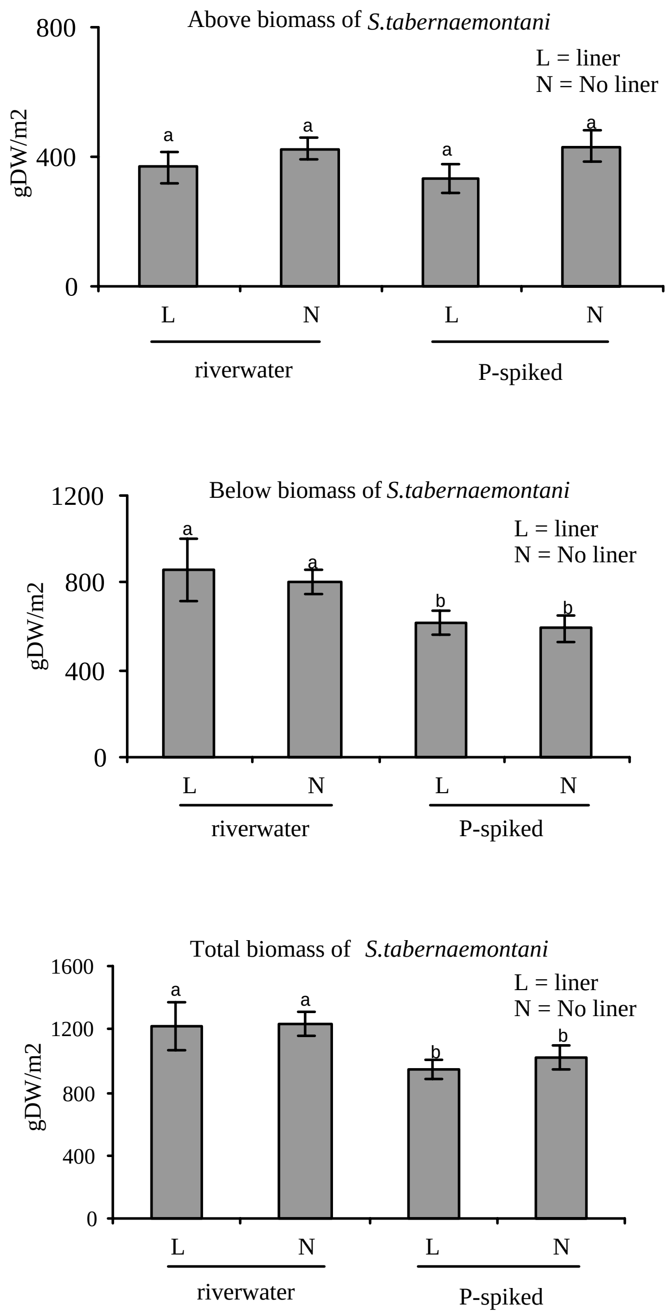
Figure 3.26 Nitrite and Nitrate of Surface Outflow and Leachate in Liner vs. No-Liner Mesocosms in 1998

Table 3.4 Number of Stems, Number of Stems Bearing Flowers, and Stem Length of *S. tabernaemontani*

Variable	Treatment			
	L + R	N + R	L + P	N + P
No. of stems	282 (20) [a]	304 (22) [a]	255 (17) [b]	289 (9) [a]
No. of stems (with flowers)	266 (17) [b]	299 (19) [a]	232 (15) [c]	284 (8) [ab]
Stem length (cm)	102.2 (2.2) [c]	112.5 (2.1) [a]	107.6 (3.6) [b]	113.4 (3.4) [a]

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

Standard error is shown following mean in ( ). Means in each row followed by the same letter are not significantly different across the treatments at the $p < 0.05$ level.



L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

Notes: 1. Bars indicate standard errors

2. The same letters among the treatments indicates no statistical difference

Figure 3.27 Biomass Production from the 1997-1998 Mesocosm Experiments

Table 3.5 ICP Analysis of Plant Tissue Material (average ± std error)

	Unit	L+R	N+R	L+P	N+P
Above groundtissue analysis					
N	%	0.93±0.03	0.98±0.02	1.04±0.02	0.96±0.07
Al	ppm	53±17	51±16	106±31	69±13
As	ppm	2.69±0.37	2.37±0.16	1.51±0.33	2.19±0.40
B	ppm	11.9±1.0	14.3±1.8	14.7±2.0	11.4±0.3
Ba	ppm	42.4±7.3	35.3±2.9	31.9±3.4	38.1±1.8
Ca	ppm	5141±493	5391±365	5703±613	4877±166
Co	ppm	0.331±0.070	0.161±0.158	0.210±0.116	0.069±0.083
Cd	ppm	ND*	ND	ND	ND
Cr	ppm	1.20±0.35	0.48±0.04	0.90±0.08	0.59±0.02
Cu	ppm	23.88±9.91	4.78±0.87	8.09±4.17	12.60±9.28
Fe	ppm	382±95	167±37	331±79	233±40
K	ppm	14777±495	13689±996	14725±1003	15424±563
Li	ppm	0.835±0.034	ND	1.167±0.204	0.813**
Mg	ppm	804±61	852±71	930±110	870±43
Mn	ppm	1543±184	1210±101	1395±169	1382±231
Mo	ppm	2.77±0.38	10.80±3.66	3.72±2.21	10.45±2.82
Na	ppm	407±69	597±88	385±63	494±45
Ni	ppm	45.2±22.6	3.7±1.1	20.3±16.0	23.3±21.6
P	ppm	1285±31	1229±59	1752±125	1661±146
Pb	ppm	13.68±3.80	7.08±0.01	13.35±11.79	8.69±4.41
S	ppm	2521±179	2216±249	2604±243	2229±239
Si	ppm	31.30±0.98	33.92±1.39	34.67±1.51	30.98±2.23
Sr	ppm	40.77±5.28	41.04±4.05	44.01±6.41	46.85±1.74
V	ppm	0.592±0.151	0.472±0.061	0.543±0.056	ND
Zn	ppm	34.69±9.95	20.30±2.24	13.01±0.42	12.98±1.25
Belowground tissue analysis					
N	%	0.53±0.04	0.52±0.04	0.55±0.02	0.54±0.04
Al	ppm	2832±745	1399±332	2560±718	1355±256
As	ppm	27.23±2.76	20.59±5.03	28.61±8.70	27.19±4.76
B	ppm	11.1±1.5	8.2±0.6	9.2±2.7	7.7±0.5
Ba	ppm	42.6±7.1	26.8±4.1	39.1±12.5	31.0±3.6
Ca	ppm	3317±447	2436±256	3135±994	2543±225
Co	ppm	1.227±0.139	1.253±0.217	1.244±0.336	1.260±0.072
Cd	ppm	3.654±0.535	2.958±0.383	3.789±1.113	3.010±0.364
Cr	ppm	4.43±0.99	3.20±0.91	4.16±1.08	2.48±0.43
Cu	ppm	8.25±0.91	7.49±0.66	7.83±2.04	8.10±0.35
Fe	ppm	14952±1527	9941±1955	13867±4291	12017±1994
K	ppm	11208±574	10543±852	7864±2030	10124±1110
Li	ppm	2.778±0.379	1.333±0.218	2.044±0.594	1.513±0.205
Mg	ppm	1486±148	1287±87	1156±320	1121±57
Mn	ppm	596±51	576±39	565±165	598±28
Mo	ppm	4.58±0.50	4.43±0.53	4.48±1.28	6.61±1.55
Na	ppm	916±28	1161±116	839±226	957±132
Ni	ppm	9.7±1.9	6.9±1.5	10.4±3.7	7.5±2.4
P	ppm	1724±198	1818±146	1391±365	1985±71
Pb	ppm	7.17±1.26	8.64±4.95	7.10±0.95	14.57±9.85
S	ppm	2088±248	1704±131	1806±567	1495±101
Si	ppm	47.03±7.91	33.75±2.79	38.10±10.49	30.51±3.09
Sr	ppm	44.85±4.13	35.51±2.98	41.39±12.45	39.99±3.35
V	ppm	7.603±1.808	4.276±0.784	7.466±2.189	4.547±0.705
Zn	ppm	45.39±10.63	26.21±2.11	29.44±9.51	25.10±1.26

The sample size was five for all treatments except L+P, of which sample size was four.
*ND indicates the concentration of the element was below the detection limit.
** indicates the number of samples detected for the element was one.
L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

Table 3.6 ICP Analysis of Surface Soil Elements (average ± std error)

	Unit	L+R	N+R	L+P	N+P
Al	ug/g	484 ±17	525 ±12	480 ±28	524 ±16
As	ug/g	0.21**	ND*	0.400 ±0.101	0.216 ±0.065
B	ug/g	1.502 ±0.167	1.378 ±0.064	1.246 ±0.113	1.259 ±0.085
Ba	ug/g	17.23 ±3.11	21.89 ±3.90	16.96 ±3.76	17.77 ±4.46
Ca	ug/g	2858 ±203	2169 ±45	3251 ±545	2745 ±263
Cd	ug/g	0.259 ±0.042	0.259 ±0.033	0.227 ±0.049	0.277 ±0.038
Co	ug/g	1.435 ±0.068	1.539 ±0.091	1.451 ±0.134	1.560 ±0.111
Cr	ug/g	0.212 ±0.020	0.210 ±0.053	0.228 ±0.012	0.245 ±0.036
Cu	ug/g	5.44 ±0.72	5.14 ±0.83	5.10 ±0.90	5.18 ±0.80
Fe	ug/g	416 ±18	414 ±31	422 ±30	421 ±23
K	ug/g	76.5 ±7.7	93.1 ±11.1	78.4 ±5.2	87.3 ±11.2
Mg	ug/g	362 ±8	369 ±10	342 ±6	351 ±7
Mn	ug/g	128 ±13	110 ±8	126 ±15	102 ±14
Mo	ug/g	0.061**	0.165 ±0.068	0.062**	0.154 ±0.035
Na	ug/g	74.0 ±3.1	73.1 ±4.2	71.8 ±4.0	73.8 ±1.2
Ni	ug/g	3.119 ±0.071	3.411 ±0.105	3.407 ±0.134	3.563 ±0.091
P	ug/g	7.130 ±0.344	8.524 ±0.519	9.218 ±1.032	11.476 ±1.335
Pb	ug/g	3.846 ±1.330	3.760 ±1.115	3.023 ±1.258	3.400 ±1.194
S	ug/g	322 ±51	221 ±41	396 ±132	372 ±88
Si	ug/g	182 ±7	189 ±4	189 ±8	192 ±4
Sr	ug/g	23.1 ±1.7	21.2 ±1.2	26.3 ±3.7	26.0 ±2.3
V	ug/g	0.989 ±0.059	0.923 ±0.048	1.159 ±0.015	1.198 ±0.068
Zn	ug/g	7.737 ±0.875	7.270 ±0.328	6.979 ±0.394	7.404 ±0.455

L = FGD Liner; N = No Liner; P = Phosphorous-Spiked River Water; R = River Water

4 FULL-SCALE FGD-LINED STUDY

4.1 Introduction

Permeability of a field compacted FGD structure is likely to be a function of the construction process, and hence the field validation of the properties obtained in the laboratory is an important part of the documentation process. In this chapter, we present the design, construction and monitoring of a full-scale testing facility, to evaluate the performance of a field-compacted FGD liner. The full-scale facility was constructed to address two critical questions about the behavior of stabilized FGD products constructed in the field, i.e. what is the permeability of a compacted engineered liner of known thickness and density, and what is the quality of the water that flows through the FGD liner.

4.2 Design of Facility

The full-scale facility was designed and constructed at The Ohio State University's Ohio Agricultural Research and Development Center (OARDC) Western Branch in South Charleston (Clark County), Ohio. This site was chosen over other university sites because it had an abundance of clay onsite that was suitable for use as a secondary or outer liner to contain the primary FGD liner. The OARDC Western Branch facility is a swine and agronomic research facility and, hence, it was decided to build a livestock manure storage facility that could be used by the center for storing swine manure after the completion of this research. The facility was designed for a capacity of approximately one million gallons (150,000 ft^3) to provide six months storage for all liquid wastes from the swine onsite. A double-layered design was chosen with compacted stabilized FGD as the primary inner liner and the onsite clay (about 80 feet of grey glacial till) as the secondary outer liner. A leachate system was designed to be placed between the primary FGD liner and secondary clay liner to collect in a sump any water passing through the FGD fill. The sump was designed so that it could be used to collect leachate samples with ease and for conducting field permeability tests on the pond liner.

The facility is essentially rectangular in shape with overall dimensions of approximately 150 feet by 250 feet (including 8-foot wide berms), as shown in Figure 4.1. Three sides of the pond were constructed at 3:1 slope and the fourth (east) side slope at 7:1. The east side slope was designed to be less steep so as to allow for easy access to the pond bottom during and after construction. Cross-sections AA and BB which are presented as Figures 4.2 and 4.3, respectively, show the final elevations of the facility. As seen in Figures 4.2 and 4.3, the pond is 9 feet deep with a liquid freeboard of 2 feet. A berm of minimum 8-foot top width was added around the periphery of the pond to minimize the inflow of surface water. The natural clay at the site provided an outer liner that was at least 5 feet thick. The leachate collection system, which consisted of corrugated high-density polyethylene (HDPE) perforated pipes (with socks) and protected against crushing using #57 washed river gravel, was placed over the re-compacted clay. The bottom of the pond was then covered with 9 inches of sand. On top of the sand layer, an 18-inch thick layer of compacted FGD material was placed. A plan view of the leachate collection system is shown in Figure 4.4. A typical detail of the perforated pipe embedded in the sand layer is shown in Figure 4.5. The proposed design of the facility was submitted to Ohio EPA for review and approval. Prior to project construction, a Permit to Install was issued by Ohio EPA for the installation of the demonstration facility (Ohio Environmental Protection Agency, 1997).

4.3 Construction of Facility

Excavation of the site began on July 30, 1997. The top layer of soil containing organic matter was removed and hauled away from the site. The re-compaction of onsite glacial till to form the secondary clay liner was completed on August 7, 1997. The onsite glacial till clay had an average moisture content of 11.6% and maximum proctor dry density of 18.6 KN/m^3 (118 lb/ft^3). A sheepsfoot roller (with vibration) was used to compact the onsite clay (refer Figure 4.6) to 99.4% of the proctor density. The laboratory permeability of the onsite compacted clay was measured to range between 3.04×10^{-7} cm/sec (9.97×10^{-9} ft/sec) and 7.24×10^{-8} cm/sec (2.37×10^{-9} ft/sec). The locations of the leachate collection system pipes were marked and excavated to a trench depth of 6 to 8 inches. A geofabric (to separate the secondary clay liner and sand particles) was spread over the clay with at least one foot of overlap at the geofabric joints. The leachate system pipes were then placed over the geofabric (see Figure 4.7). The leachate collection system was connected to an 18-inch diameter vertical sump (20 feet height). About 50 tons of crushed #57 washed river gravel was then placed around and on top of the leachate collection system pipes to avoid crushing due to later compaction of FGD on top of it. The crushed river gravel can be seen on the right hand side of Figure 4.8. The bottom of the facility was then covered with approximately 300 tons of silicious round natural fine sand (refer Figure 4.8). The permeability of the sand used in the drainage layer was evaluated in the laboratory to be 3.12×10^{-3} cm/sec (1.02×10^{-4} ft/sec). A layer of geofabric was laid over the sand layer.

Lime and fly ash enriched stabilized FGD material was delivered by truck (starting August 11, 1997) from American Electric Power's Conesville Station near Coshocton, Ohio (Figure 4.9) to the site. Placement and compaction of FGD in 4-6 inch lifts on top of the geofabric layer were accomplished using two dozers and one sheepsfoot roller (see Figures 4.10 and 4.11). Approximately 2,700 tons of lime-enriched stabilized FGD material was used in the construction of the primary liner. The fly ash to filter cake ratio of the FGD material ranged from 1.48:1 to 2.40:1 with an average ratio of 1.81:1. The lime content varied from 6.79% to 8.44% with an average lime content of 7.98%. The moisture content of the FGD material received at the site during construction ranged from 49% to 62%, while the proctor dry density varied between 9.6 kN/m^3 (61 lb/ft^3) and 11.6 kN/m^3 (74 lb/ft^3). Wet weather during the liner placement resulted in several delays but construction at the site was completed by August 26, 1997. The site was smooth rolled before completion of the project (Figure 4.12). Filling of the pond with water from an existing nearby pond began on September 12, 1997 and was completed on September 23, 1997. Figure 4.13 is a photograph of the partially filled facility. The pond was filled with water up to a depth of approximately 9 feet as shown in Figure 4.14.

To avoid coring holes in the full-scale FGD liner for obtaining permeability samples, several FGD test pads were constructed in vicinity of the full-scale facility. Four rectangular test pads (approximately 15 feet wide, 25-30 feet long and 3-4 feet deep) were installed. Each test pad was initially backfilled with 6 inches of sand to provide a permeable layer for drainage. The remainder of the excavation was filled with stabilized compacted FGD material. Due to the small size of the test pads compared to the large dimensions of the sheepsfoot roller, adequate compaction of the FGD material in the test pads could not be obtained. Three of the test pads (TP1, TP2, and TP3) were constructed using the 1.25:1 (FA:FC) and 8% lime mix, which was the typical mix used in the construction of the full-scale facility. TP4 was constructed using a 0.8:1 (FA:FC) and 4% lime FGD mix, which is the typical material generated at the power plant. This weaker mix was not used in the construction of the full-scale facility. An outline of the test pads constructed is shown in Table 4.1. Each of the test pad was instrumented for Boutwell field permeability testing apparatuses (Boutwell, 1992). The instrumentation and monitoring of the test pads was conducted by BBC & M Engineering of Columbus, Ohio. A detailed report prepared and submitted by them is attached as Appendix C.

The actual cash cost of constructing the full-scale facility was estimated to be $46,623.50. The FGD material was made available at the site free of charge by American Electric Power's Conesville power plant. Thus the actual cash cost does not include the cost of adding additional lime to the material (approximately $13,500) and the associated transportation costs (estimated to be $25,000) for transporting the FGD material from Coshocton to the South Charleston project site. The cash cost of sand, gravel, drainage pipes, geofabric, and other miscellaneous materials was $4567.50. The cash cost of construction of the facility was $42,056. The construction cost included equipment and operator costs for a backhoe (Kebelco 300), two bull dozers (Kamatsu D-6 and John Deere J 450), roller (sheepsfoot / smooth), trenching machine, Bobcat loader, two dump trucks, rotovator with farm tractor, and a farm tractor with front end loader.

4.4 Monitoring of Facility

The facility was used to store water for the first year. In early September of 1998, some of the water was replaced with swine manure. Since then swine manure has continued to be added and removed from the facility on a regular basis depending on the manure storage vs. field spreading needs of the research farm. Monitoring of the site for field permeability and water quality was carried out for a period of 2 years and 5 months (September 1997 through January 2000). The average monitoring frequency was three months. The monitoring program consisted of two main activities:

1) *Field Permeability Testing:* Full-scale falling head permeability tests on the facility were conducted by lowering the water level in the sump to create a head difference across the FGD liner. The amount of time taken to increase the water in the sump to specific levels was observed. Knowing the thickness of the FGD liner and its plan view area, the effective permeability of the field compacted FGD-lined facility was calculated (refer Figure 4.15).
2) *Water Quality Monitoring Program:* Testing of water samples from the pond, the sump, and a well about 1,000 feet from the site was carried out on a regular basis. Samples were collected in 250 ml polyethylene bottles that had been prewashed with acid and triple rinsed with deionized water. Acidified samples were obtained by adding 2.5% nitric acid by volume to the samples in the field. Filtered samples were passed through a 0.45 μm filter. The water quality analysis was performed by the Star Laboratory of The Ohio State University's School of Natural Resources at OARDC, Wooster. Tests conducted on the water samples included pH, electrical conductivity, alkalinity, acidity, total dissolved solids, 24 elements by

Inductively Coupled Plasma (ICP) Emission Spectrometry Mineral Analysis, 4 anions using Ion Chromatography (IC) Analysis, and ammonia as well as nitrogen by Micro-Kjeldahl Distillation. Although the vicinity well was about 1,000 feet from the site and not necessarily hydrologically connected to the site, the well samples were investigated so that potential contamination of the farm water supply from the FGD lined facility could be detected.

4.5 Monitoring Observations and Discussion

4.5.1 Permeability

After filling the full-scale facility with water, the actual field permeability of the FGD liner was measured by lowering the water level in the sump and taking readings of the water level rising in the sump at various time intervals (refer to Figure 4.15). The permeability coefficients were calculated using the bottom area of the pond as the effective leaching area for the FGD-liner. Table 4.2 shows the effective coefficients of permeability obtained from full-scale permeability tests conducted on the pond facility. The permeability coefficient values listed in Table 4.2 are the average of several test readings that were measured at each curing time. The full-scale permeability of the facility was evaluated to be 9.1×10^{-7} cm/sec (2.9×10^{-8} ft/sec) at a curing time of one month. The permeability coefficient continued to reduce over time (due to curing of FGD) and has stabilized at approximately 4×10^{-7} cm/sec (1×10^{-8} ft/sec). The FGD permeability coefficient data range obtained from the full-scale tests is comparable to typical clays used in the construction of compacted liners. The data presented in Table 4.2 includes the effect of freeze-thaw cycling on the actual permeability of the FGD liner. The actual area over which water flows through the FGD liner is greater than the bottom area of the pond (i.e., a significant amount of water may flow through the sides of the pond). Hence the full-scale permeability values presented in Table 4.2 should be taken to be an upper bound to the actual permeability of the field-compacted FGD liner. The addition of swine manure to the facility (at 370 days of curing and thereafter) did not affect the actual permeability of the liner.

The specific seepage rate (seepage volume below liner per unit liner area per unit time) for the full-scale facility can be obtained by multiplying the actual average coefficient of permeability with the hydraulic gradient across the liner. If no secondary liner were present at the site, the specific seepage rate for the 9 feet deep manure storage pond having an 18-inch thick FGD liner was calculated to be 0.0952 $in^3/in^2/day$. Although currently Ohio does not provide guidance on maximum design seepage rate from lagoons, many states do specify maximum seepage rate values. For example, Kansas state regulations (Ham et al., 1998, 1999,2000) allow for a maximum seepage rate of 0.25 $in^3/in^2/day$. Specific seepage rates less than 0.1 $in^3/in^2/day$ are considered to be very low seepage values. The value for the full-scale FGD lined pond facility is 0.0952 $in^3/in^2/day$. Hence, it can be concluded that if there was no secondary clay liner constructed for the facility (as would be the norm for typical FGD-lined pond and manure storage facilities), the seepage rate loss from such FGD facilities would be very low.

The actual field permeability data obtained from the full-scale pond tests was compared with a) laboratory tests conducted on several laboratory compacted samples collected during pond construction, b) laboratory tests conducted on field compacted samples cored from test pads installed at the site, and c) field permeability tests (Boutwell) conducted on the test pads TP1, TP2, and TP3. TP4 was not considered for comparison because this test pad was constructed using FGD material that was lower in lime content and fly ash to filter cake ratio compared to the material used in the construction of the full-scale facility. Figure 4.16 shows the time history comparison of the full-scale permeability test values with averaged permeability coefficients obtained from a) laboratory tests on laboratory compacted samples, b) field tests (Boutwell) conducted on test pads, and c) laboratory tests conducted on samples cored from test pads. All the test procedures showed decreasing permeability coefficient with increasing curing time. It was observed that the laboratory compacted samples had permeability coefficients which were an order of magnitude lower than the full-scale testing values. Permeability values obtained from Boutwell tests and cored samples tested in the laboratory were in close agreement with each other but were one to three orders of magnitude higher than the full-scale tests. The test pad sample permeability values (Boutwell tests and cored sample testing) indicated a large scatter in the data. The permeability coefficients varied from 10^{-4} cm/sec ($3x10^{-6}$ ft/sec) to 10^{-7} cm/sec ($3x10^{-9}$ ft/sec) with average permeability value in range of 10^{-5} cm/sec ($3x10^{-7}$ ft/sec). This may be due to the unsuitable compaction achieved for the test pads. Furthermore, the Boutwell test procedure relates infiltration rate with permeability coefficient by assuming certain direction and boundary conditions of flow, which are nearly impossible to control in the field. However, it is important to note that the actual measured field permeability values of the full-scale FGD liner are an order of magnitude higher than laboratory measured values.

4.5.2 Water Quality

Water quality monitoring of the site was conducted by collecting water samples from the pond, sump (leachate) and a vicinity well. The first baseline water samples were collected on

September 12, 1997 before any water was added to the facility. Only well and sump samples were collected. After the pond had been filled with water on September 23, 1997, water samples were collected from the pond, sump and well on a regular basis. The water sampling program was conducted while the pond held water (until September 1998) and beyond, at which time swine manure was added to the facility on a regular basis (project monitoring ended January, 2000). It needs to be noted that the addition and removal of swine manure from the FGD-lined facility continued throughout the duration of the project. Swine manure was added to the facility in Summer and Winter and partially removed in Fall for spreading on farm fields as per the agronomic needs of crops.

All samples were tested for several constituents and properties including pH, electrical conductivity, alkalinity, acidity, total dissolved solids, aluminum, arsenic, boron, barium, calcium, cadmium, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorous, lead, sulfur, selenium, silica, silver, vanadium, zinc, chloride, phosphate, sulfate, nitrate, ammonia and nitrogen.

Table 4.3 lists the measured concentration levels of the above listed elements. The time history for various water quality measurement parameters is shown in Figure 4.17 through Figure 4.51. The concentration level of various analytes in the sump (leachate) increased suddenly following the filling of the facility with water. Thereafter, the concentration levels reduced rapidly. The leachate from the FGD lined facility needs to meet OEPA's non-toxic criteria (DSW 0400.007, 1994). All the non-toxic parameters (arsenic, barium, cadmium, chromium, lead, selenium) measured for the FGD facility while holding water and swine manure were much lower than

OEPA's non-toxic criteria. For many elements measured (barium, cadmium, chromium, and nitrate), the leachate concentration levels were generally lower than the National Primary Drinking Water Regulations (NPDWR).

Arsenic concentration levels for the pond and sump samples were very low for the first year (Figure 4.23). Upon addition of swine manure to the facility (in early September, 1998), the concentration level of arsenic in the pond has increased. However, the sump samples indicate little increase in arsenic concentrations (which are slightly higher than the NPDWR level of 0.05 μg/ml). Arsenic levels in the sump and pond have always been lower than OEPA's non-toxic regulatory value of 1.5 μg/ml. Barium concentrations were significantly lower than the primary drinking water standards (Figure 4.25). Cadmium concentrations (Figure 4.27) have generally been at the detection limit and much lower than the NPDWR for the monitoring duration. The sudden increase in all cadmium concentration values for 10/2/98 seems to be erroneous. Chromium concentration in sump and pond samples has been lower than NPDWR except when the facility was just filled with water (Figure 4.28). Copper concentrations have been significantly lower than the USEPA Action Level of 1.3 μg/ml and NSDWR limit of 1.0 μg/ml (Figure 4.29). Lead concentration levels for sump and pond have been at the detection limit (Figure 4.39). The lead level in well samples is elevated due to the use of lead pipes to convey water from the bottom of the well to the sampling point. Selenium concentration levels have generally been slightly above the NPDWR value of 0.05 μg/ml (Figure 4.41). A sudden increase in all selenium measurements for 3/16/99 seems erroneous. Nitrate, a highly soluble form of nitrogen, had low concentration for pond and sump samples, except when the facility was filled with water (Figure 4.49). In general, nitrate levels in the leachate are extremely low compared to NPDWR value of 10 μg/ml.

It can be observed from Figure 4.17 that the pH of the well sample has been decreasing slightly according to seasonal groundwater variations. The pH of the pond sample was within the Ohio Secondary Maximum Contaminant Level (OSMCL). The pH of the sump water rose sharply to 12 on filling the facility with water and has been dropping since then. The last pH level reading for the sump was 8.4, which is within the OSMCL range of 7.0 to 10.5 and slightly lower than the National Secondary Drinking Water Regulations (NSDWR) upper limit of 8.5. The dissolved aluminum concentrations in the sump samples increased significantly during the filling of the pond (Figure 4.22). However soon after filling the facility, the sump aluminum concentrations dropped significantly and have generally been around the NSDWR limit. Total iron levels for the pond and sump samples are quite low (Figure 4.31). Total manganese level for the sump is lower than or comparable to the NSDWR limit value (Figure 4.35). However, pond samples indicate a steady increase in manganese concentrations due to the addition of swine manure to the pond. Silver concentrations reduced significantly after filling of facility with water and for the last year or so have been at the detection limit (Figure 4.43). Concentration level of zinc in sump and pond was much lower than NSDWR limit for the complete duration of project monitoring (Figure 4.45). On filling the pond, the chloride concentration in the sump increased to about four times the NSDWR limit, but has decreased since then to a level lower or slightly higher than the NSDWR regulation limit (Figure 4.46). Sulfate levels in the sump have generally been within the NSDWR limit (Figure 4.48). It should be noted that the leachate from the full-scale FGD-lined facility meets most of the NSDWR limits. NSWDR limits are non-enforceable non-health related guidelines regulating potential contaminants that may cause cosmetic or aesthetic effects in drinking water. From a regulatory perspective, the leachate from the FGD material is not required to meet any of the NSDWR limit values, yet the leachate concentration levels measured from the FGD lined facility are generally lower or comparable to the NSDWR limits for most potential contaminants of concern.

Boron, elevated levels of which can be phytotoxic to plant growth, generally had lower concentration levels in the sump than the pond (Figure 4.24). This may be due to absorption of some boron by the FGD liner. Calcium level in the pond has continued to increase rapidly, while the sump indicates much lower concentration levels, which have not increased significantly (Figure 4.26). Phosphorous concentration in the sump increased on addition of swine manure to the facility (Figure 4.38) but the sump phosphorous levels have remained close to the detection limit. Phosphate levels in the pond increased on addition of swine manure, while the concentration levels in the sump remained relatively unchanged (Figure 4.47) at the detection limit. Ammonia levels increased in pond with addition of swine manure. This resulted in an increase in the concentration of ammonia in the leachate (Figure 4.50). Ammonia, which can be converted to soluble nitrate in the presence of oxygen (non-saturated conditions), may be a concern during the cleaning and removal of manure storage facilities (irrespective of whether the facility is constructed with clay or FGD). The concentrations of highly soluble constituents, such as nitrates and phosphates, were observed to be relatively low in the sump.

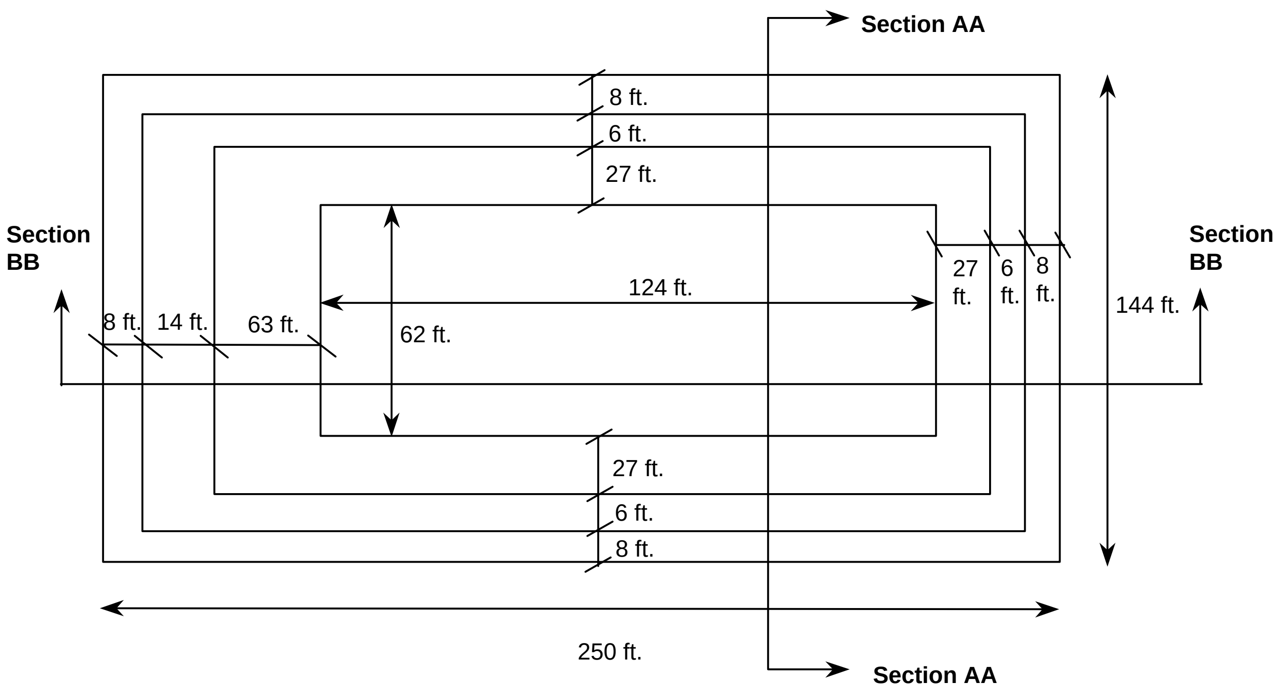


Figure 4.1 Plan View of Facility (not to scale)

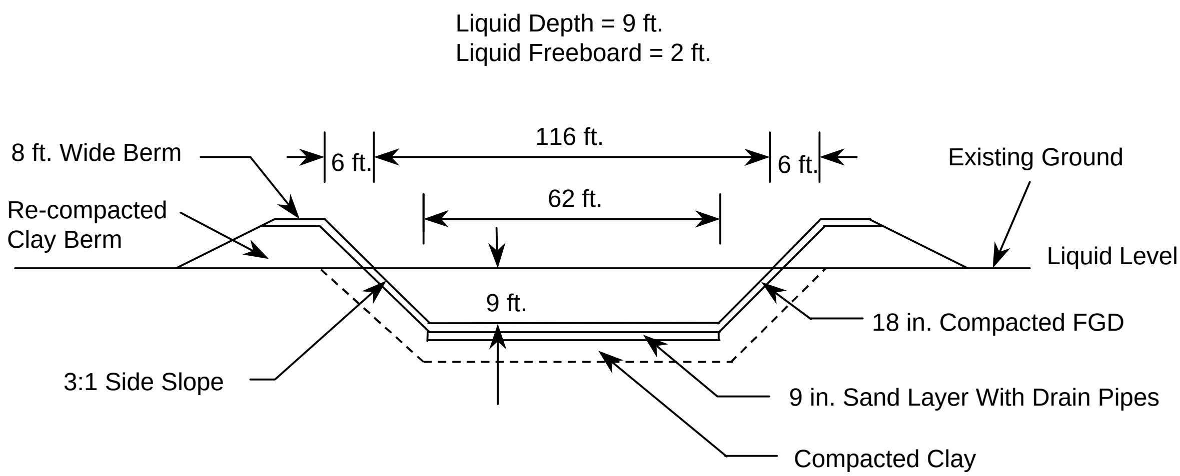


Figure 4.2 Section AA of Facility (not to scale)

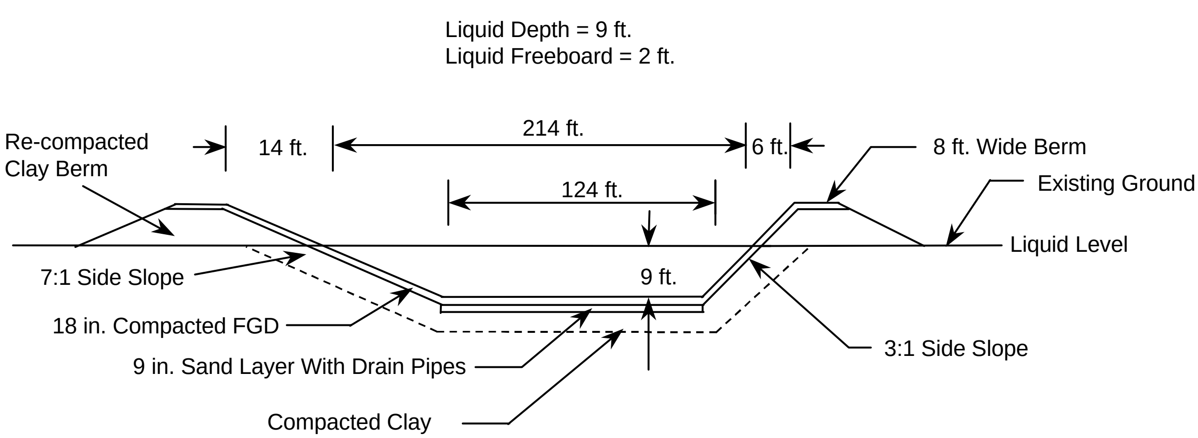


Figure 4.3 Section BB of Facility (not to scale)

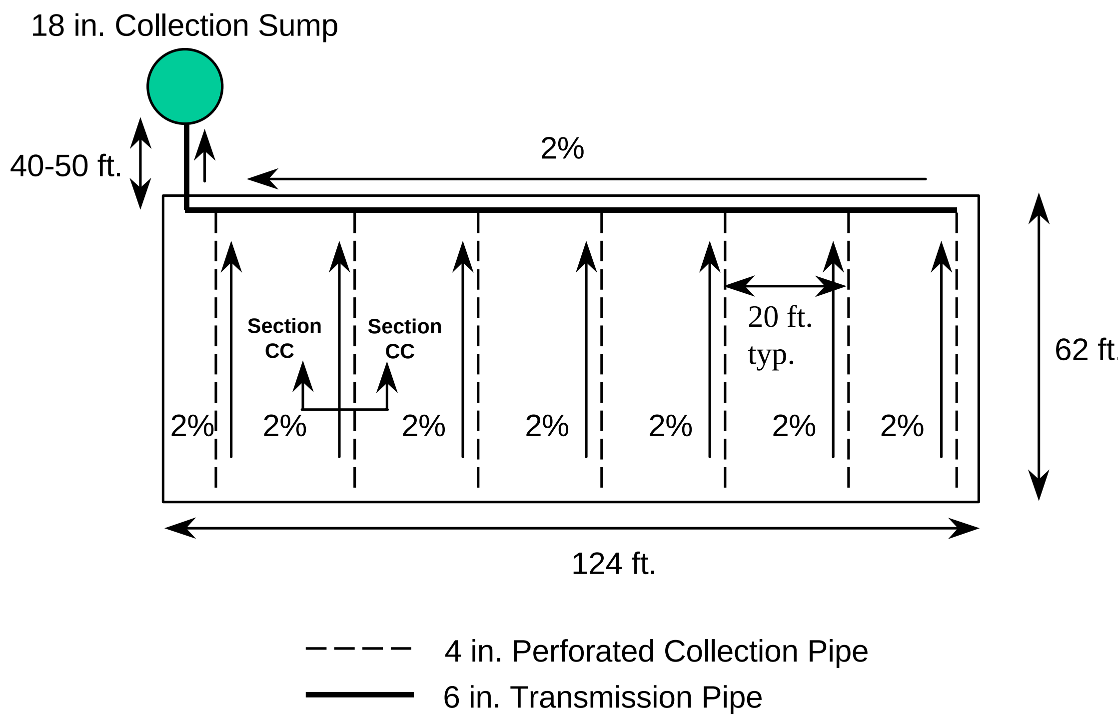


Figure 4.4 Leachate Collection System Layout (not to scale)

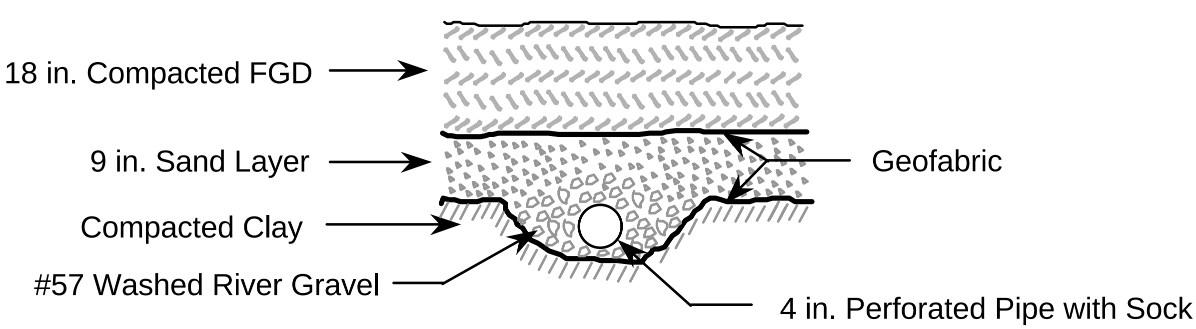


Figure 4.5 Section CC of Facility (not to scale)

Figure 4.6 Compaction of Onsite Clay

Figure 4.7 Typical Leachate System Collection

Figure 4.8 Spreading of Sand

Figure 4.9 Truck Unloading FGD

Figure 4.10 Spreading the FGD

Figure 4.11 Compacting FGD on a Side Slope

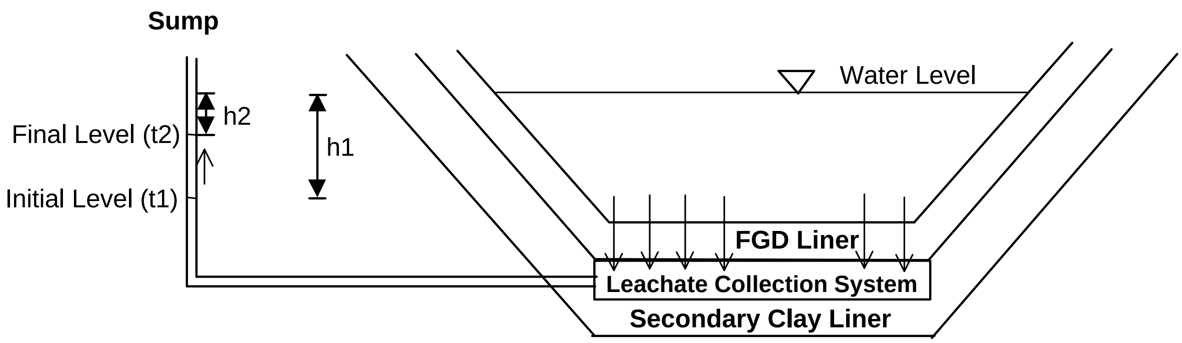
Figure 4.12 Final Smooth Rolling of FGD

Figure 4.13 Facility Being Filled With Water

Figure 4.14 Facility Filled With Water

Table 4.1 FGD Test Pads Constructed

Pad Number	Thickness of Sand (inches)	Stabilized FGD			
		Thickness (inches)	Approx. FA:FC ratio	Approx. Lime content (%)	Moisture content (%)
TP1	6	27	1.25:1	8	62
TP2	6	36	1.25:1	8	69
TP3	6	30	1.25:1	8	58
TP4	6	36	0.8:1	4	84



$$k = \frac{L}{(t2 - t1)} \frac{a}{A} \ln\left(\frac{h1}{h2}\right)$$

L = Thickness of FGD liner
a = Area of sump
A = Effective area of FGD liner

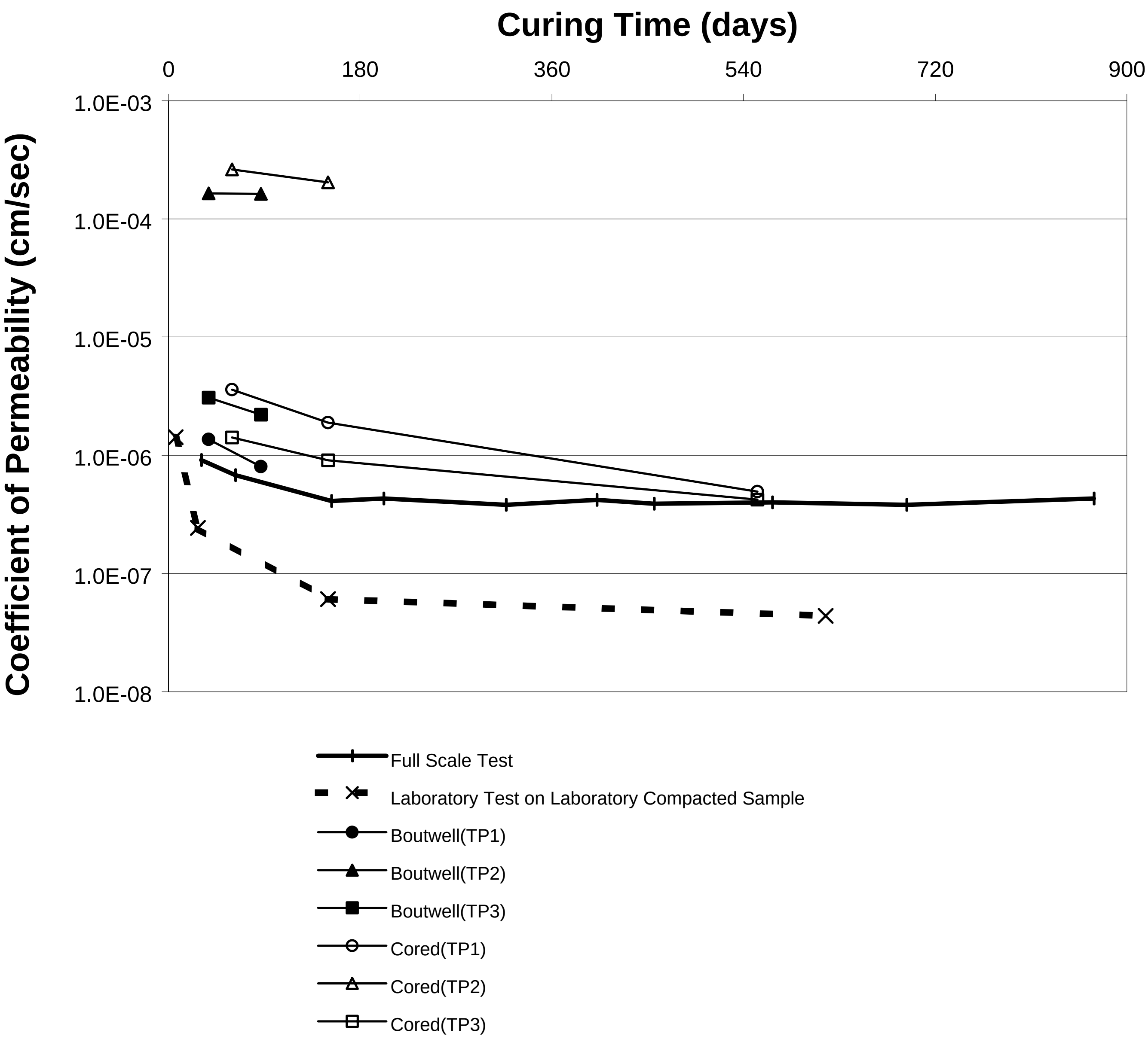
Figure 4.15 Full Scale Permeability Test (not to scale)

Table 4.2 Full Scale Permeability Test Results

Curing Time (days)	Coefficient of Permeability * (cm/sec)
31	9.1×10^{-7}
63	6.8×10^{-7}
153	4.1×10^{-7}
202	4.3×10^{-7}
317	3.8×10^{-7}
402	4.2×10^{-7}
456	3.9×10^{-7}
567	4.0×10^{-7}
693	3.8×10^{-7}
869	4.3×10^{-7}

1 cm/sec = 0.0328 ft/sec

* Effective area of FGD liner = Bottom area of pond



1 cm/sec = 0.0328 ft/sec

Figure 4.16 Comparison of Permeability Test Methods

Table 4.3 Water Quality Monitoring

Date Sample Collected	Location of Sample	pH	Electrical Conductivity (µS/cm)	Alkalinity (mg/L $CaCO_3$)	Acidity (meq/L $CaCO_3$)	Residue of Evaporation at 180°C (mg/L)
9/12/97	Sump	7.94	1,460	227.83	0.14	1,103
	Well	8.25	702	331.06	0.02	427
9/28/97	Sump	12.05	6,894	772.64	0.00	3,703
	Pond	8.39	780	82.24	0.06	607
	Well	8.62	629	317.50	0.00	430
1/26/98	Sump	11.23	3,260	254.76	0.00	1,962
	Pond	7.85	988	44.97	0.04	764
	Well (Tap)	7.96	642	301.36	0.00	420
3/16/98	Sump	11.28	2,954	251.24	0.00	1,736
	Pond	7.57	1,166	42.99	0.04	952
	Well	7.77	662	310.60	0.00	426
7/9/98	Sump	9.12	2,537	143.69	0.00	1,499
	Pond	8.22	1,659	31.06	0.00	1,420
	Well	7.54	683	308.19	0.13	400
10/2/98	Sump	9.52	2,650	167.28	0.00	1,661
	Pond	8.98	2,030	158.59	0.00	2,604
	Well	7.65	640	305.06	0.18	396
11/25/98	Sump	9.77	2,905	138.41	0.00	1,777
	Pond	6.68	2,244	137.74	0.49	2,156
	Well	7.64	672	310.39	0.13	404
3/16/99	Sump	7.62	1,756	312.44	0.28	1,227
	Pond	7.02	2,134	57.77	0.20	1,913
	Well	7.40	701	299.02	0.26	434
7/20/99	Sump	8.92	2,721	71.24	0.00	1,707
	Pond (Center)	8.24	3,556	1,436.48	0.00	2,600
	Pond (Edge)	8.35	3,295	1,363.44	0.00	2,511
	Well	7.54	650	304.88	0.00	383
1/12/00	Sump	8.38	3,079	283.80	0.00	1,863
	Pond	7.56	4,726	1,433.79	1.76	2,850
	Well	7.35	672	303.90	0.00	399
Regulatory Standards		6.6 - 8.5** 7.0 - 10.5$				

* Primary Drinking Water Standard
** Secondary (Non-health related) Drinking Water Standard
*** Action Level
$ Ohio Secondary Maximum Contaminant Level
# Ohio Non-Toxic Criteria (OEPA DSW 0400.007 policy)

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Al (Dissolved) (μg/ml)	As (μg/ml)	B (μg/ml)	Ba (μg/ml)	Ca (μg/ml)
9/12/97	Sump	0.157	<0.035	0.059	0.100	169.11
	Well	0.248	<0.035	0.214	0.080	51.30
9/28/97	Sump	5.505	0.049	1.154	0.035	39.84
	Pond	0.713	<0.035	0.742	0.028	114.77
	Well	0.151	<0.035	0.204	0.078	53.13
1/26/98	Sump	1.033	<0.035	0.552	0.027	36.85
	Pond	0.489	<0.035	0.635	0.028	132.89
	Well (Tap)	<0.040	<0.035	0.203	0.058	43.05
3/16/98	Sump	0.737	<0.035	0.455	0.030	48.30
	Pond	0.305	<0.035	0.692	0.031	161.68
	Well	<0.040	<0.035	0.205	0.069	45.43
7/9/98	Sump	0.809	<0.035	0.374	0.017	2.87
	Pond	0.403	<0.035	0.952	0.049	268.39
	Well	<0.040	<0.035	0.187	0.077	44.95
10/2/98	Sump	0.465	<0.035	0.478	0.018	2.60
	Pond	0.118	0.046	1.435	0.043	337.53
	Well	0.048	<0.035	0.173	0.072	48.22
11/25/98	Sump	0.270	0.038	0.779	0.026	10.57
	Pond	0.090	0.086	1.753	0.010	363.88
	Well	<0.027	<0.035	0.194	0.079	50.25
3/16/99	Sump	<0.040	<0.045	0.354	0.077	98.63
	Pond	0.080	0.052	1.271	0.046	384.44
	Well	<0.040	<0.045	0.208	0.071	47.10
7/20/99	Sump	0.106	<0.045	0.840	0.042	42.75
	Pond (Center)	0.158	0.114	2.071	0.008	187.01
	Pond (Edge)	0.147	0.074	2.035	0.012	174.95
	Well	0.050	<0.045	0.194	0.073	51.00
1/12/00	Sump	0.197	0.059	1.670	0.089	96.48
	Pond	1.291	0.124	2.762	0.049	301.88
	Well	0.081	<0.045	0.233	0.078	50.18
Regulatory Standards		0.05 - 0.2**	0.05* 1.5#		2.0* 60.0#	

* Primary Drinking Water Standard
** Secondary (Non-health related) Drinking Water Standard
*** Action Level
$ Ohio Secondary Maximum Contaminant Level
# Ohio Non-Toxic Criteria (OEPA DSW 0400.007 policy)

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	**Location of Sample**	**Cd** (μg/ml)	**Cr** (μg/ml)	**Cu** (μg/ml)	**Fe (Dissolved)** (μg/ml)	**Fe (Total)** (μg/ml)
9/12/97	Sump	<0.001	0.080	0.018	0.026	0.043
	Well	<0.001	0.125	0.026	0.260	0.267
9/28/97	Sump	<0.001	0.087	0.014	0.120	0.150
	Pond	<0.001	0.188	0.019	0.081	0.048
	Well	<0.001	0.127	0.034	0.301	0.039
1/26/98	Sump	0.001	<0.005	<0.004	0.022	0.019
	Pond	<0.001	<0.005	<0.004	0.065	0.142
	Well (Tap)	0.001	<0.005	0.039	1.315	1.313
3/16/98	Sump	0.001	<0.005	<0.004	0.008	<0.006
	Pond	<0.001	<0.005	<0.004	0.008	0.016
	Well	<0.001	<0.005	<0.004	0.539	0.546
7/9/98	Sump	<0.001	<0.005	<0.004	<0.006	<0.006
	Pond	<0.001	0.006	<0.004	<0.006	<0.006
	Well	<0.001	0.006	<0.004	0.026	0.083
10/2/98	Sump	0.0042	<0.002	<0.002	<0.010	<0.010
	Pond	0.0035	<0.002	0.050	0.074	0.097
	Well	0.0029	<0.002	<0.002	0.263	0.302
11/25/98	Sump	<0.001	<0.002	0.003	<0.010	0.037
	Pond	<0.001	<0.002	0.003	0.242	0.323
	Well	0.001	0.002	<0.002	0.183	0.187
3/16/99	Sump	<0.002	<0.005	<0.010	<0.010	0.024
	Pond	<0.002	<0.005	<0.010	0.024	0.048
	Well	<0.002	<0.005	<0.010	0.534	0.603
7/20/99	Sump	<0.002	<0.005	<0.010	<0.010	0.034
	Pond (Center)	<0.002	0.006	0.015	0.072	0.675
	Pond (Edge)	<0.002	0.007	0.026	0.080	0.947
	Well	<0.002	0.006	0.080	0.374	9.205
1/12/00	Sump	<0.002	<0.005	0.021	0.104	0.153
	Pond	<0.002	0.009	0.217	2.000	1.757
	Well	<0.002	<0.005	<0.010	0.539	2.524
Regulatory Standards		0.005*	0.1*	1.0**		
		0.15#	3.0#	1.3***		

* Primary Drinking Water Standard
** Secondary (Non-health related) Drinking Water Standard
*** Action Level
$ Ohio Secondary Maximum Contaminant Level
\# Ohio Non-Toxic Criteria (OEPA DSW 0400.007 policy)

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	K (μg/ml)	Mg (μg/ml)	Mn (Dissolved) (μg/ml)	Mn (Total) (μg/ml)	Na (μg/ml)
9/12/97	Sump	42.53	68.42	0.114	0.115	26.79
	Well	2.26	31.74	0.019	0.012	43.08
9/28/97	Sump	1069.29	0.34	<0.002	<0.002	317.55
	Pond	44.28	18.33	0.003	0.002	32.94
	Well	2.80	32.98	0.011	0.044	42.17
1/26/98	Sump	581.90	0.53	<0.002	<0.002	189.08
	Pond	59.33	10.87	0.002	0.002	28.75
	Well (Tap)	2.00	35.77	0.075	0.072	45.58
3/16/98	Sump	480.11	0.43	<0.002	<0.002	158.07
	Pond	64.35	11.27	<0.002	0.002	30.71
	Well	1.75	35.05	0.089	0.094	45.46
7/9/98	Sump	451.83	0.06	<0.002	<0.002	139.55
	Pond	81.97	8.14	<0.002	<0.002	32.65
	Well	1.74	33.27	0.054	0.048	45.15
10/2/98	Sump	447.32	0.17	<0.001	<0.001	143.53
	Pond	122.06	17.90	0.044	0.054	48.41
	Well	2.56	30.08	0.002	0.002	38.29
11/25/98	Sump	499.17	0.19	<0.001	0.001	163.07
	Pond	141.70	18.88	0.073	0.074	55.44
	Well	2.19	30.69	0.002	0.002	41.22
3/16/99	Sump	256.82	37.46	0.028	0.028	55.10
	Pond	128.71	13.05	0.012	0.020	46.31
	Well	1.47	34.99	0.060	0.058	45.34
7/20/99	Sump	484.12	4.68	<0.002	0.002	159.76
	Pond (Center)	389.20	61.22	0.017	0.136	121.93
	Pond (Edge)	366.22	57.73	0.015	0.175	136.73
	Well	1.54	33.27	0.030	0.036	43.14
1/12/00	Sump	412.23	26.87	0.052	0.060	172.05
	Pond	407.73	68.28	0.410	0.395	159.53
	Well	2.03	36.77	0.093	0.098	50.58
Regulatory Standards					0.05**	

* Primary Drinking Water Standard
** Secondary (Non-health related) Drinking Water Standard
*** Action Level
$ Ohio Secondary Maximum Contaminant Level
\# Ohio Non-Toxic Criteria (OEPA DSW 0400.007 policy)

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Ni (µg/ml)	P (Total) (µg/ml)	Pb (µg/ml)	S (Total) (µg/ml)	Se (µg/ml)
9/12/97	Sump	0.006	0.044	<0.020	137.26	<0.100
	Well	0.008	0.043	<0.020	20.18	<0.100
9/28/97	Sump	0.007	0.075	<0.020	228.92	<0.100
	Pond	0.007	0.054	<0.020	126.76	<0.100
	Well	0.003	0.054	<0.020	20.45	<0.100
1/26/98	Sump	<0.009	<0.030	<0.020	183.96	<0.100
	Pond	<0.009	<0.030	<0.020	146.95	<0.100
	Well (Tap)	<0.009	0.083	0.029	20.16	<0.100
3/16/98	Sump	<0.009	0.042	<0.020	176.41	<0.100
	Pond	<0.009	<0.030	<0.020	175.99	<0.100
	Well	<0.009	0.034	0.023	20.40	<0.100
7/9/98	Sump	<0.009	<0.030	<0.020	149.93	<0.100
	Pond	<0.009	0.098	<0.020	263.87	<0.100
	Well	<0.009	0.118	0.021	19.65	<0.100
10/2/98	Sump	<0.005	<0.020	<0.020	154.37	<0.100
	Pond	0.009	1.131	<0.020	337.15	<0.100
	Well	<0.005	0.030	<0.020	18.32	<0.100
11/25/98	Sump	<0.005	0.073	<0.020	179.26	<0.100
	Pond	<0.005	1.600	<0.020	374.67	<0.100
	Well	<0.005	0.029	0.029	19.44	<0.100
3/16/99	Sump	<0.010	<0.100	<0.020	149.31	0.187
	Pond	0.012	0.370	<0.020	382.24	0.341
	Well	<0.010	<0.100	0.034	20.58	0.573
7/20/99	Sump	<0.010	<0.100	<0.020	224.45	<0.100
	Pond (Center)	<0.010	7.448	<0.020	96.81	<0.100
	Pond (Edge)	0.011	6.024	<0.020	92.45	<0.100
	Well	<0.010	<0.100	<0.020	21.39	<0.100
1/12/00	Sump	<0.010	0.812	<0.020	216.48	<0.100
	Pond	0.013	50.453	<0.020	208.23	<0.100
	Well	<0.010	<0.100	<0.020	19.70	<0.100
Regulatory Standards				0.015***		0.05*
				1.5#		1.0#

* Primary Drinking Water Standard
** Secondary (Non-health related) Drinking Water Standard
*** Action Level
$ Ohio Secondary Maximum Contaminant Level
\# Ohio Non-Toxic Criteria (OEPA DSW 0400.007 policy)

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Si (µg/ml)	Ag (µg/ml)	V (µg/ml)	Zn (µg/ml)
9/12/97	Sump	2.383	<0.008	0.010	0.043
	Well	3.872	<0.008	<0.005	0.271
9/28/97	Sump	6.037	0.104	0.035	<0.005
	Pond	0.935	0.012	0.056	<0.005
	Well	4.052	0.008	0.059	<0.005
1/26/98	Sump	3.374	0.044	0.021	0.009
	Pond	0.508	0.018	0.004	<0.005
	Well (Tap)	3.405	0.010	0.965	<0.005
3/16/98	Sump	3.169	0.028	0.008	<0.005
	Pond	0.426	0.018	<0.004	<0.005
	Well	3.869	0.008	0.261	<0.005
7/9/98	Sump	1.675	<0.008	<0.004	0.531
	Pond	0.893	<0.008	<0.004	0.623
	Well	1.998	<0.008	0.165	0.933
10/2/98	Sump	3.476	<0.003	0.011	<0.001
	Pond	4.039	0.008	0.010	0.055
	Well	3.787	0.006	<0.005	0.035
11/25/98	Sump	3.715	0.004	0.020	<0.001
	Pond	3.863	<0.001	0.035	<0.001
	Well	3.881	0.004	0.016	<0.001
3/16/99	Sump	1.929	<0.005	<0.010	<0.005
	Pond	1.495	<0.005	0.013	<0.005
	Well	2.569	<0.005	<0.010	0.095
7/20/99	Sump	1.091	<0.050	<0.010	<0.005
	Pond (Center)	4.196	<0.050	0.026	0.019
	Pond (Edge)	4.093	<0.050	0.034	0.037
	Well	2.121	<0.050	<0.010	0.029
1/12/00	Sump	2.646	<0.050	0.016	0.039
	Pond	8.633	<0.050	0.038	0.598
	Well	4.751	<0.050	<0.010	0.239
Regulatory Standards			0.10**		5.0**

* Primary Drinking Water Standard
** Secondary (Non-health related) Drinking Water Standard
*** Action Level
$ Ohio Secondary Maximum Contaminant Level
# Ohio Non-Toxic Criteria (OEPA DSW 0400.007 policy)

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	Location of Sample	Cl- (μg/ml)	PO_4- (μg/ml)	SO_4- (μg/ml)	NO_3- (μg/ml)
9/12/97	Sump	85.38	0.00	125.25	11.41
	Well	6.91	0.00	21.82	0.00
9/28/97	Sump	976.92	53.71	182.11	0.81
	Pond	16.80	0.00	104.46	0.17
	Well	5.77	0.00	18.95	0.26
1/26/98	Sump	480.08	1.36	185.05	0.41
	Pond	32.69	0.00	141.25	0.51
	Well (Tap)	5.46	0.00	20.45	0.25
3/16/98	Sump	377.50	0.00	171.19	0.33
	Pond	34.33	5.51	183.79	0.35
	Well	5.18	0.00	20.63	0.00
7/9/98	Sump	38.93	0.00	262.31	0.00
	Pond	239.67	0.00	120.82	0.00
	Well	4.83	0.00	16.00	0.00
10/2/98	Sump	381.08	0.00	159.67	0.00
	Pond	82.71	0.00	364.31	0.82
	Well	5.80	0.00	17.48	0.14
11/25/98	Sump	462.53	0.00	197.75	0.00
	Pond	83.85	3.86	421.48	0.14
	Well	5.25	0.43	18.63	0.00
3/16/99	Sump	59.28	0.00	155.68	3.78
	Pond	84.88	0.18	397.69	0.25
	Well	5.08	0.00	19.01	0.00
7/20/99	Sump	346.77	<0.10	199.19	<0.10
	Pond (Center)	226.34	6.58	71.71	<0.10
	Pond (Edge)	219.00	3.94	69.16	<0.10
	Well	13.30	<0.10	29.95	<0.10
1/12/00	Sump	362.14	<0.10	219.16	<0.10
	Pond	249.30	23.78	183.35	<0.10
	Well	5.36	<0.10	18.69	0.39
Regulatory Standards		250**		250**	10*

* Primary Drinking Water Standard
** Secondary (Non-health related) Drinking Water Standard
*** Action Level
$ Ohio Secondary Maximum Contaminant Level
# Ohio Non-Toxic Criteria (OEPA DSW 0400.007 policy)

Table 4.3 (contd.) Water Quality Monitoring

Date Sample Collected	**Location of Sample**	**Ammonia (NH4 as μg N / ml)**	**Total Nitrogen (μg N / ml)**
9/12/97	Sump	1.80	13.21
	Well	0.00	0.00
9/28/97	Sump	43.02	43.83
	Pond	0.57	0.74
	Well	0.87	1.13
1/26/98	Sump	29.68	30.09
	Pond	0.08	0.59
	Well (Tap)	0.00	0.25
3/16/98	Sump	25.28	25.61
	Pond	0.08	0.43
	Well	0.08	0.08
7/9/98	Sump	16.80	16.80
	Pond	0.40	0.40
	Well	0.00	0.00
10/2/98	Sump	23.00	23.00
	Pond	10.25	11.07
	Well	0.30	0.44
11/25/98	Sump	24.20	24.20
	Pond	0.00	0.14
	Well	0.50	0.50
3/16/99	Sump	1.00	4.78
	Pond	0.00	0.25
	Well	0.40	0.40
7/20/99	Sump	24.21	24.21
	Pond (Center)	115.71	115.71
	Pond (Edge)	109.53	109.53
	Well	0.00	0.00
1/12/00	Sump	58.25	58.25
	Pond	250.04	250.04
	Well	1.06	1.45

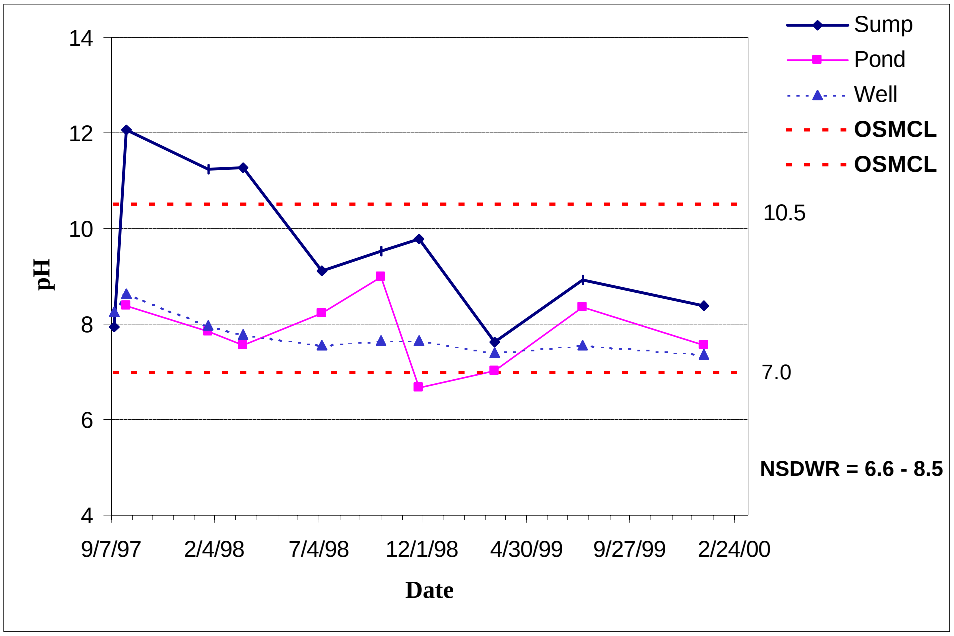


Figure 4.17 pH of Sump, Pond, and Well Samples

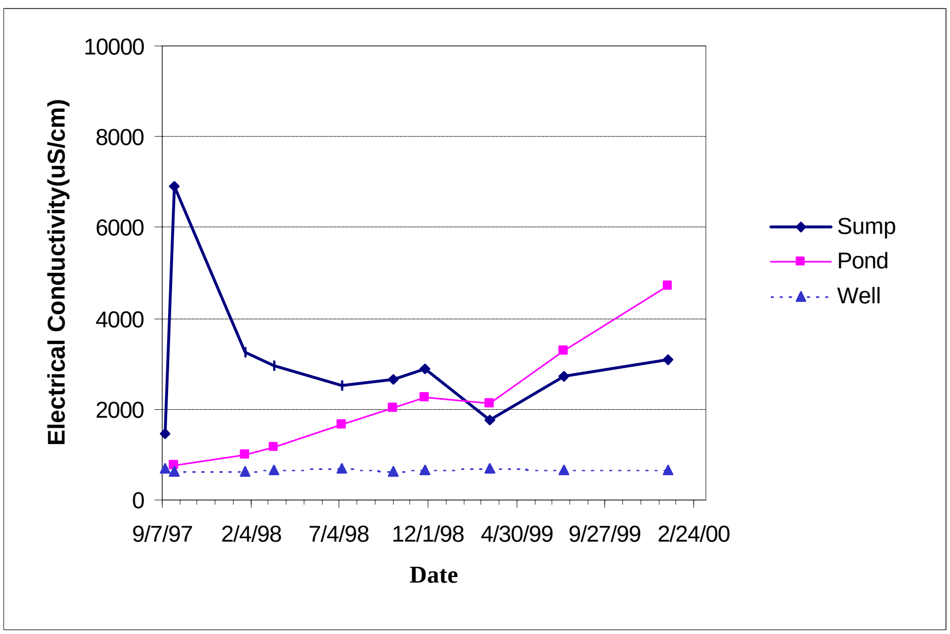


Figure 4.18 Electrical Conductivity of Sump, Pond, and Well Samples

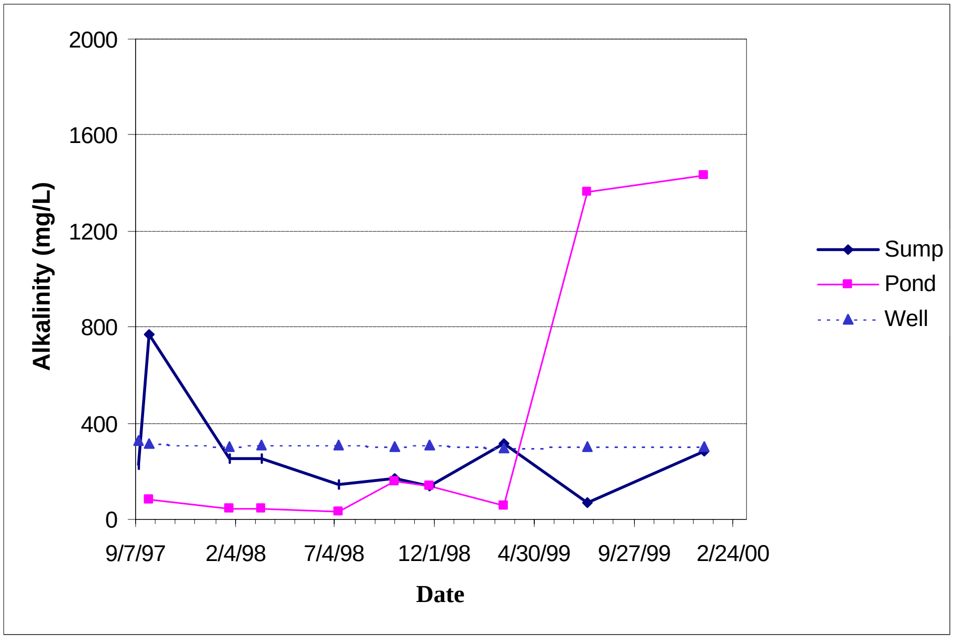


Figure 4.19 Alkalinity of Sump, Pond, and Well Samples

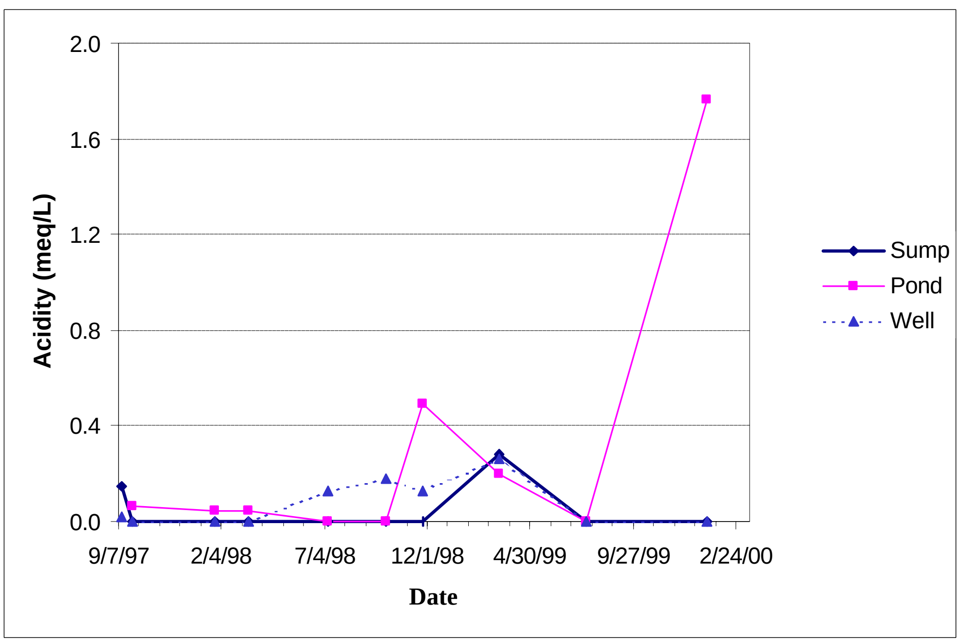


Figure 4.20 Acidity of Sump, Pond, and Well Samples

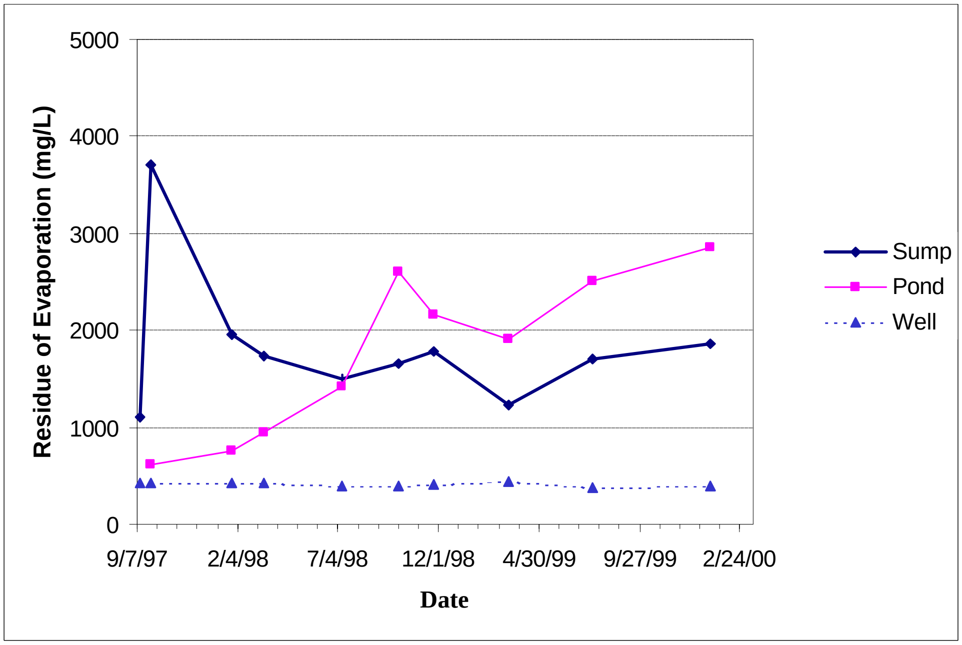


Figure 4.21 Residue of Evaporation of Sump, Pond, and Well Samples

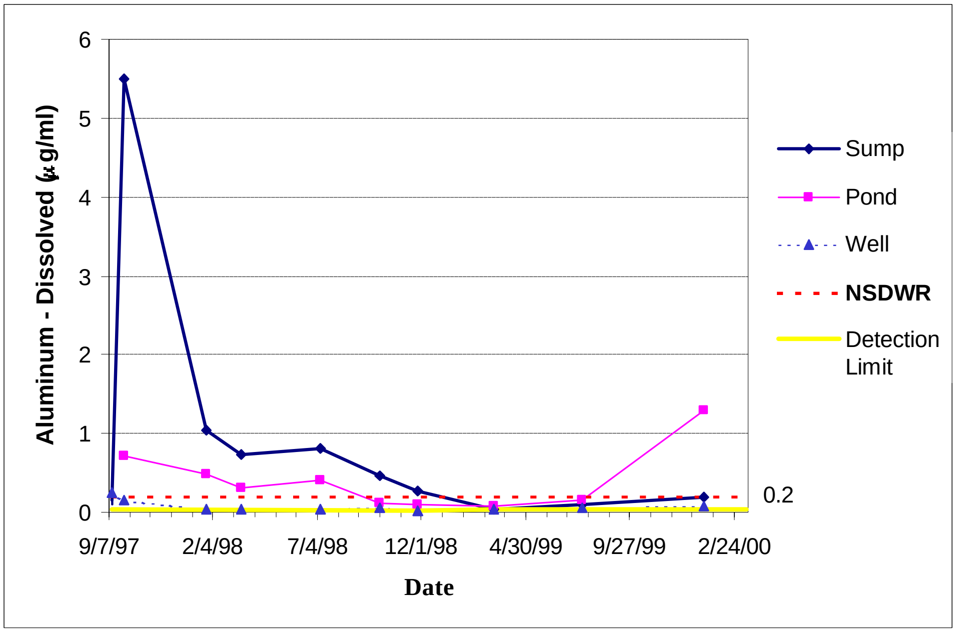


Figure 4.22 Concentration of Dissolved Aluminum for Sump, Pond, and Well Samples

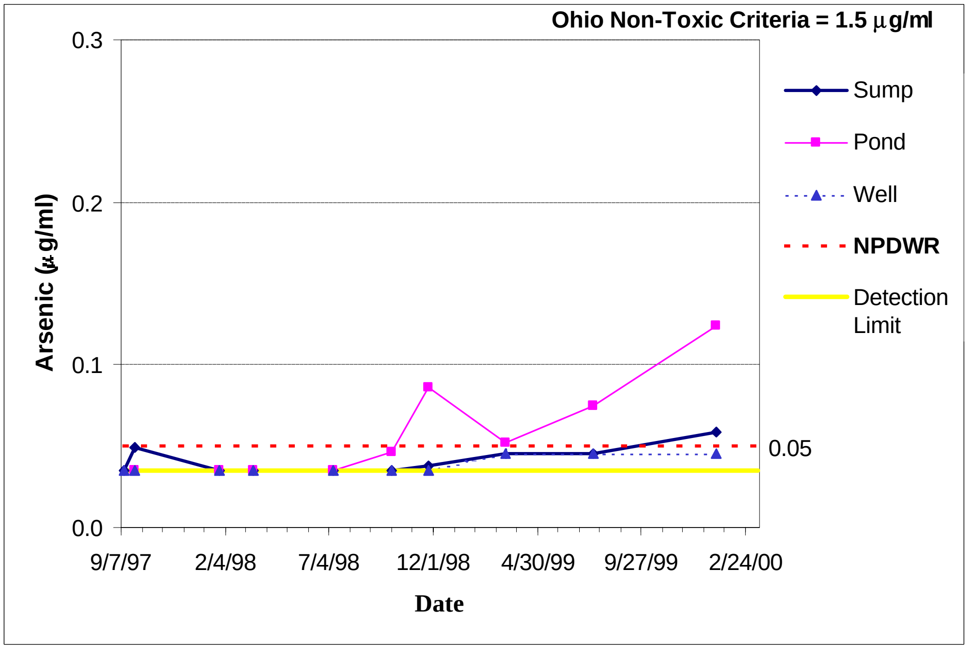


Figure 4.23 Concentration of Arsenic for Sump, Pond, and Well Samples

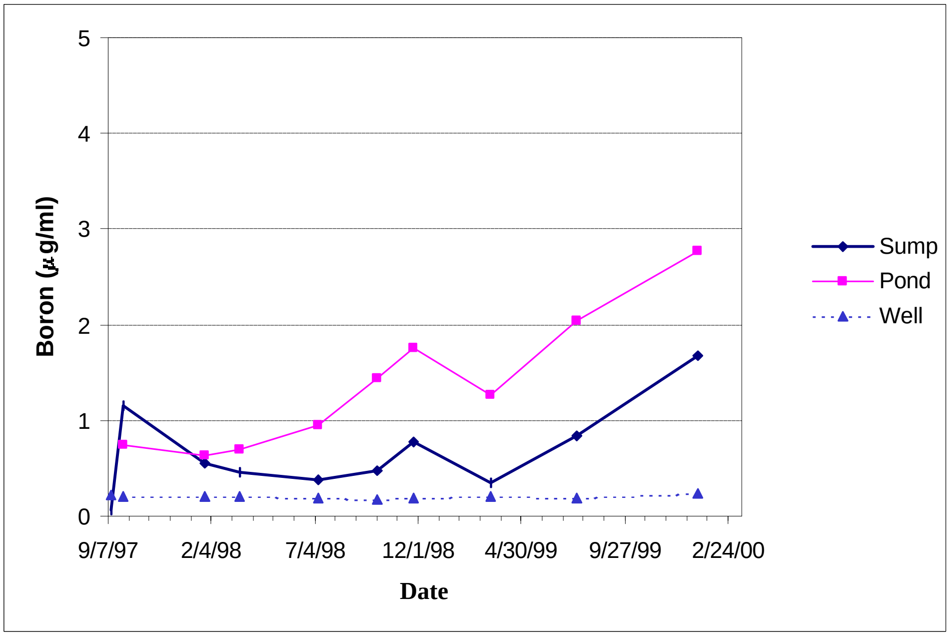


Figure 4.24 Concentration of Boron for Sump, Pond, and Well Samples

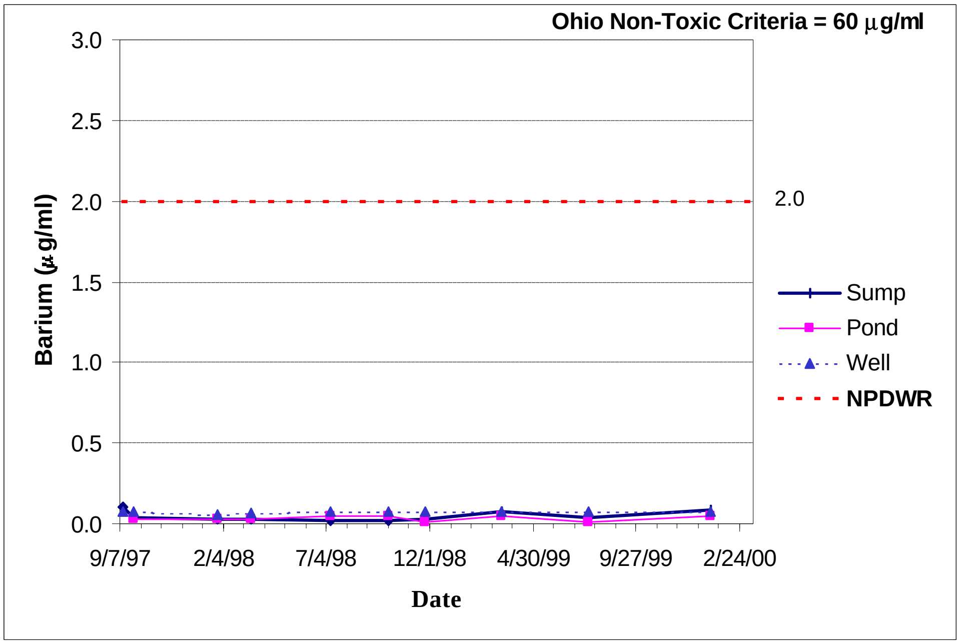


Figure 4.25 Concentration of Barium for Sump, Pond, and Well Samples

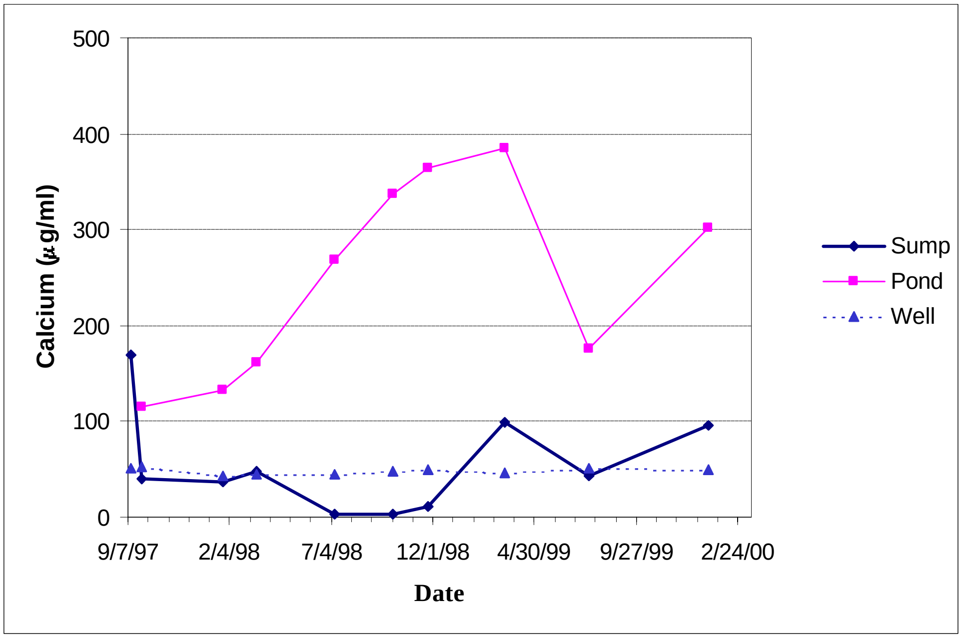


Figure 4.26 Concentration of Calcium for Sump, Pond, and Well Samples

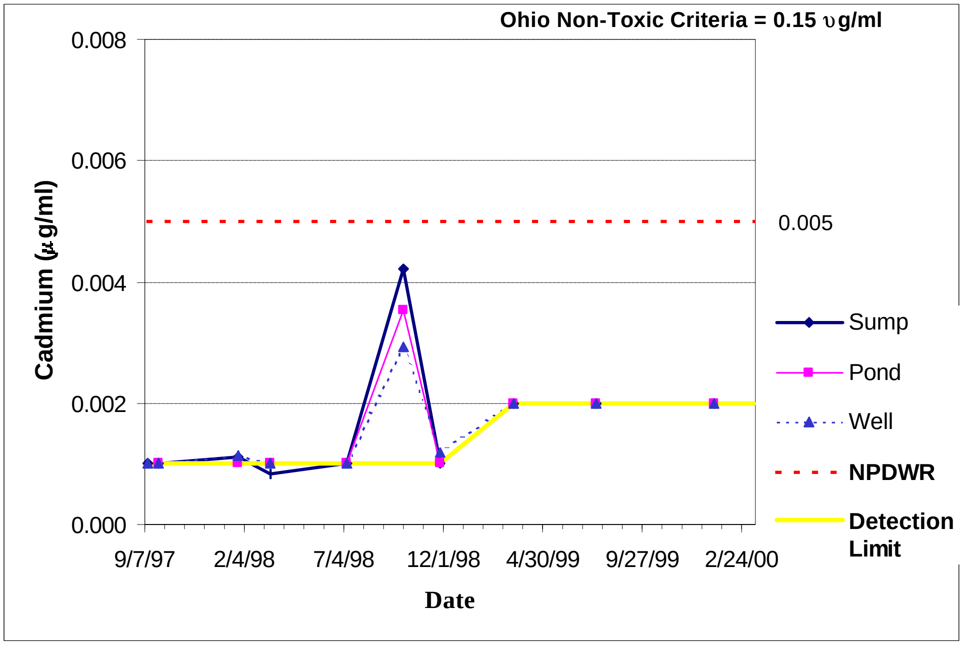


Figure 4.27 Concentration of Cadmium for Sump, Pond, and Well Samples

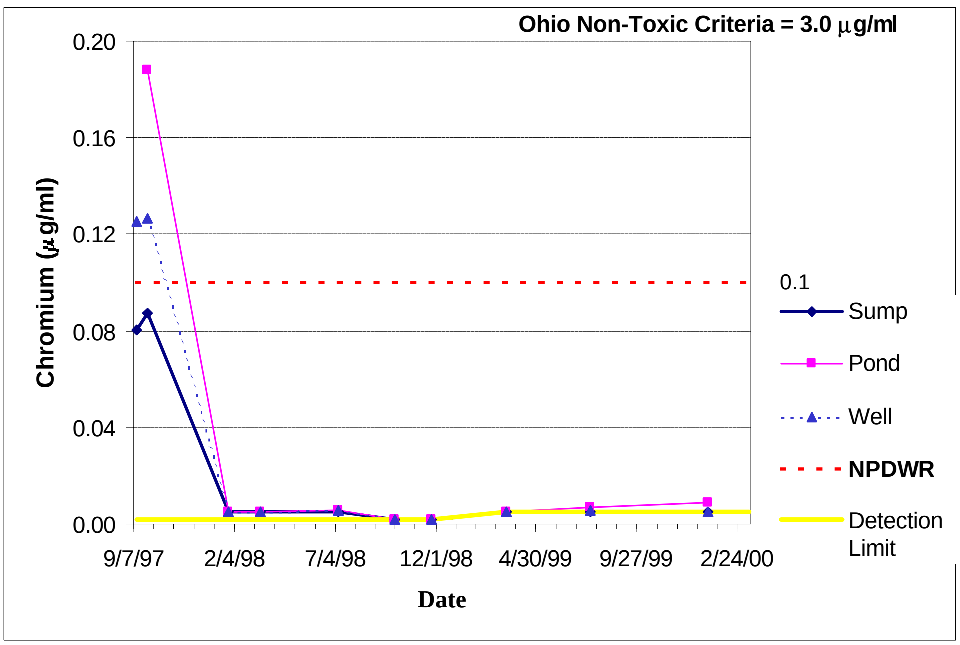


Figure 4.28 Concentration of Chromium for Sump, Pond, and Well Samples

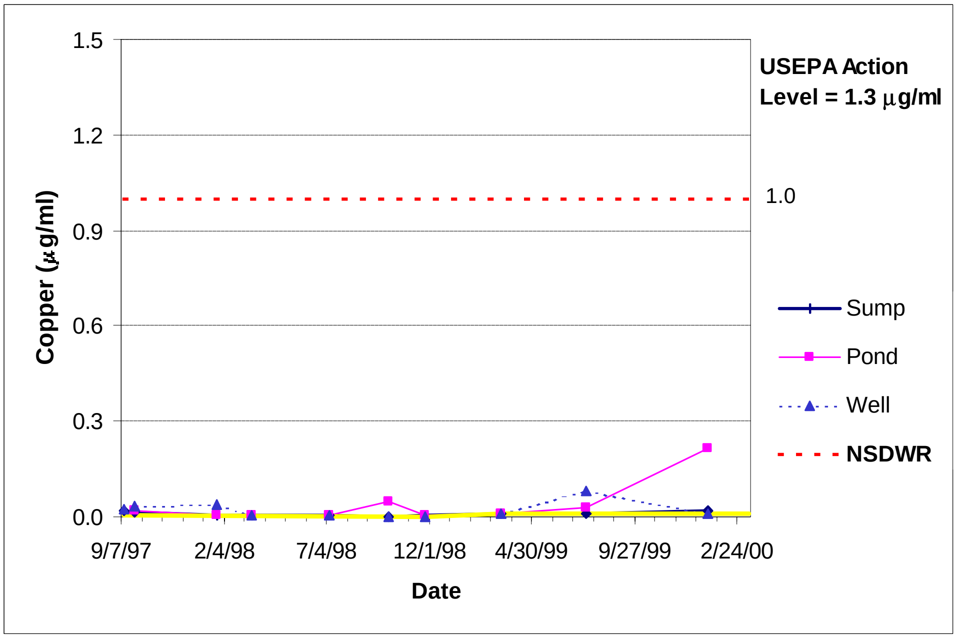


Figure 4.29 Concentration of Copper for Sump, Pond, and Well Samples

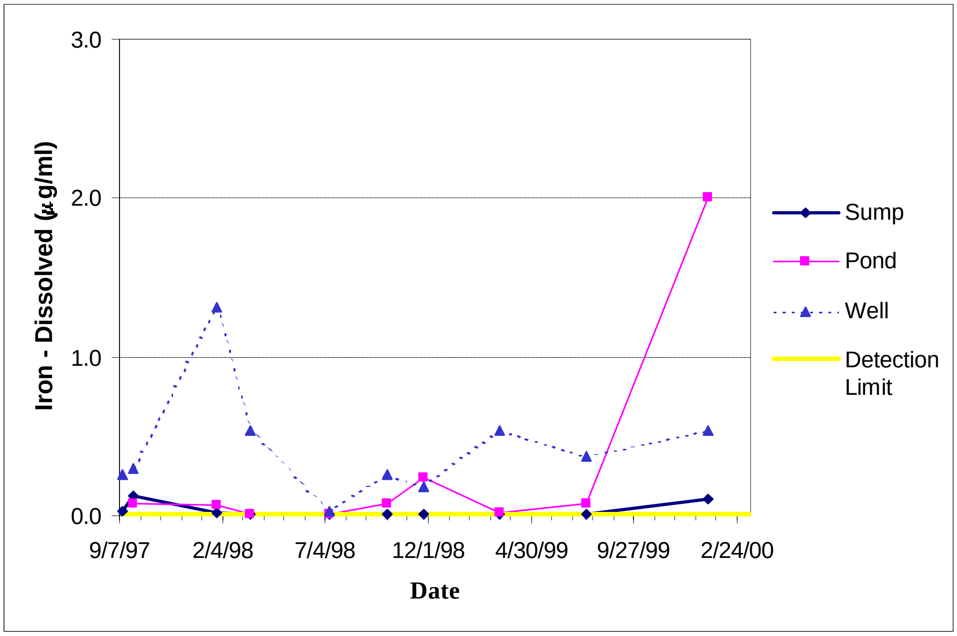


Figure 4.30 Concentration of Dissolved Iron for Sump, Pond, and Well Samples

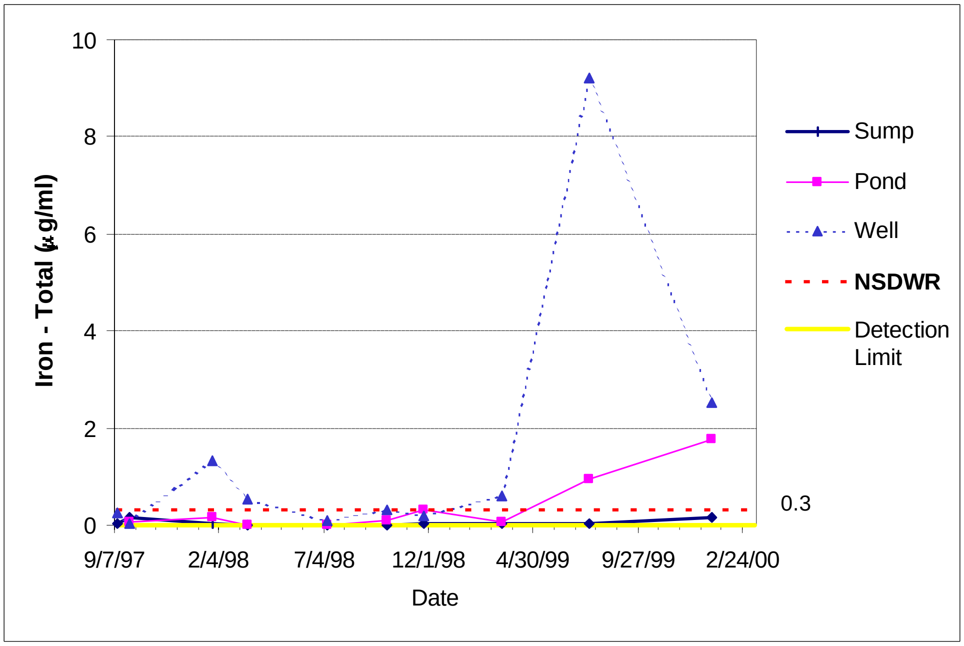


Figure 4.31 Concentration of Total Iron for Sump, Pond, and Well Samples

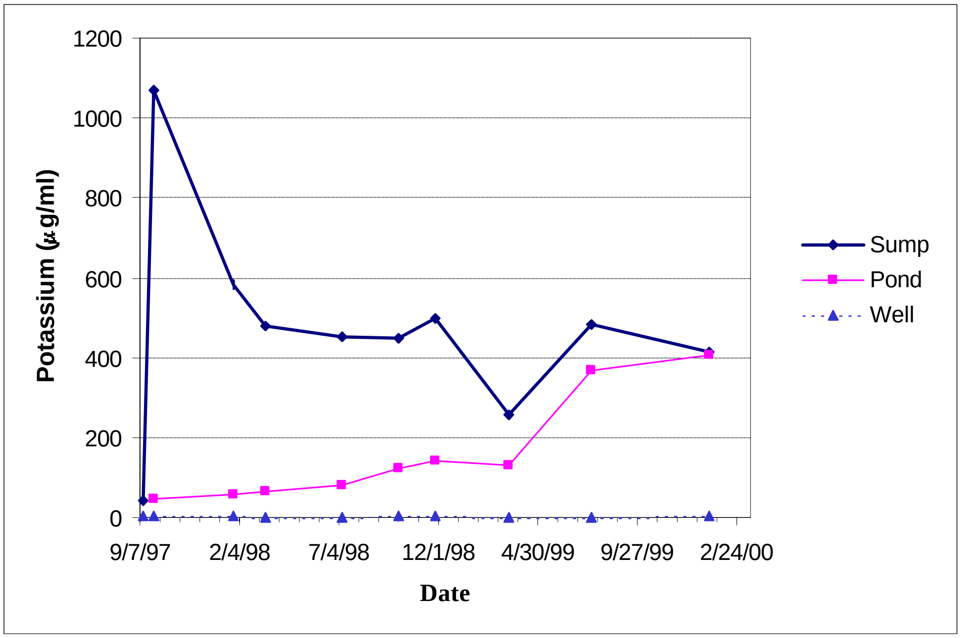


Figure 4.32 Concentration of Potassium for Sump, Pond, and Well Samples

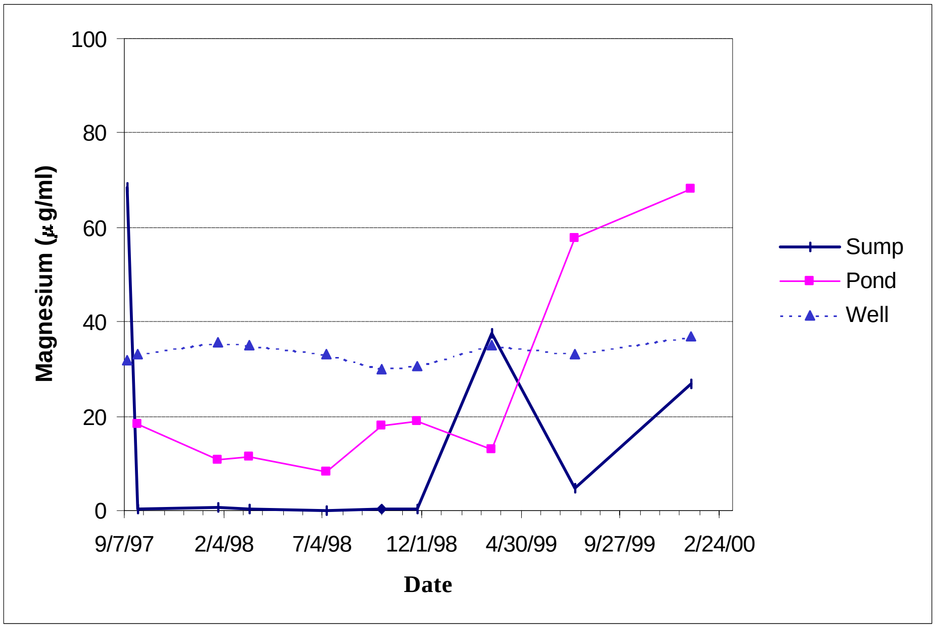


Figure 4.33 Concentration of Magnesium for Sump, Pond, and Well Samples

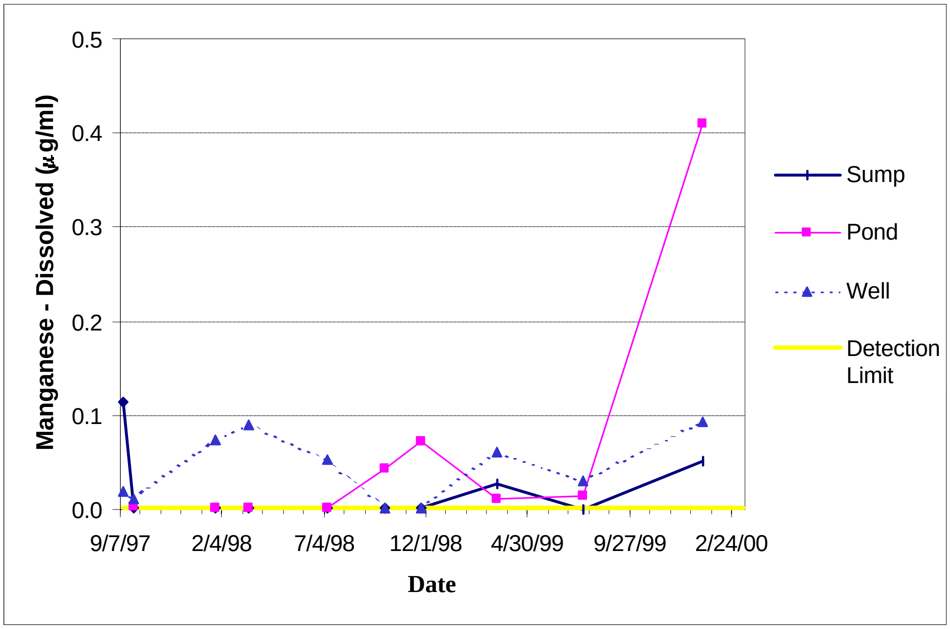


Figure 4.34 Concentration of Dissolved Manganese for Sump, Pond, and Well Samples

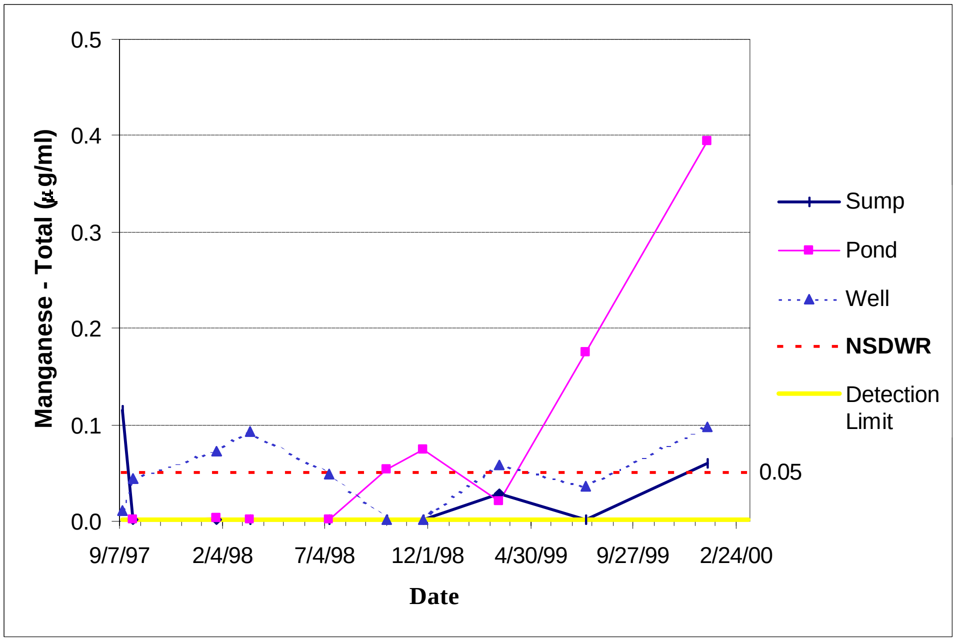


Figure 4.35 Concentration of Total Manganese for Sump, Pond, and Well Samples

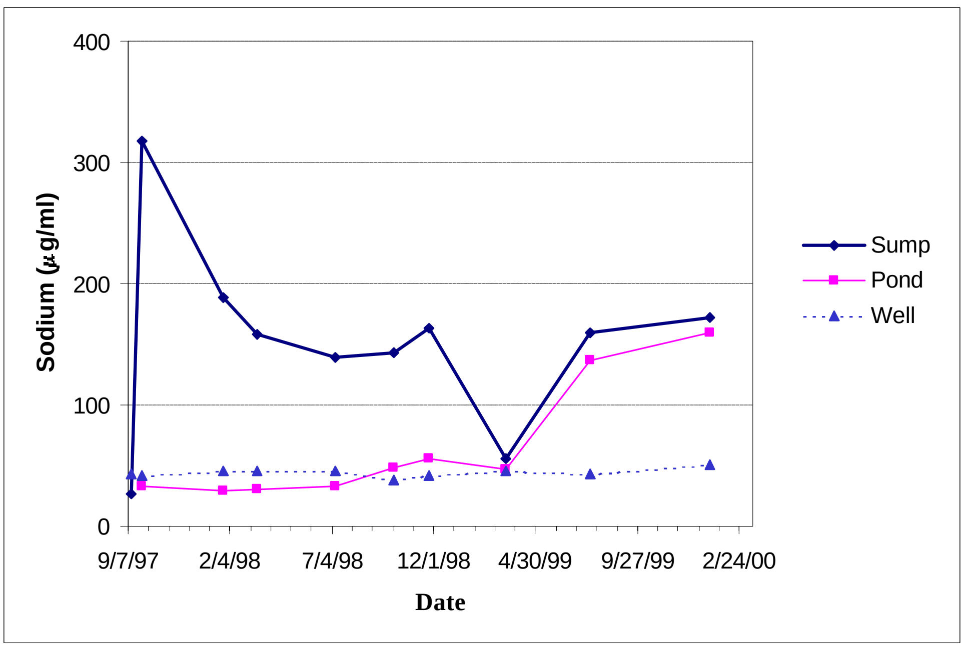


Figure 4.36 Concentration of Sodium for Sump, Pond, and Well Samples

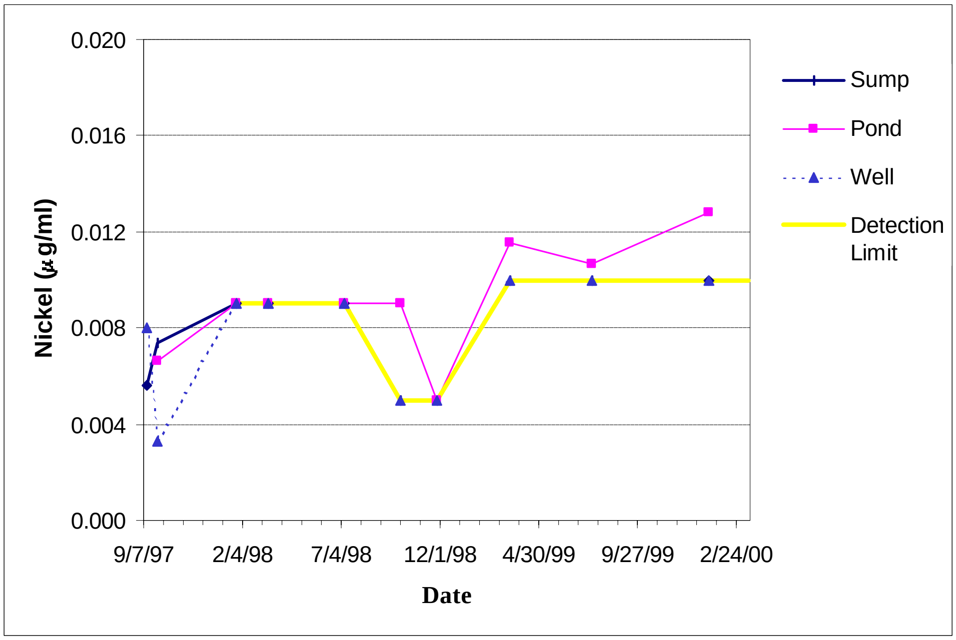


Figure 4.37 Concentration of Nickel for Sump, Pond, and Well Samples

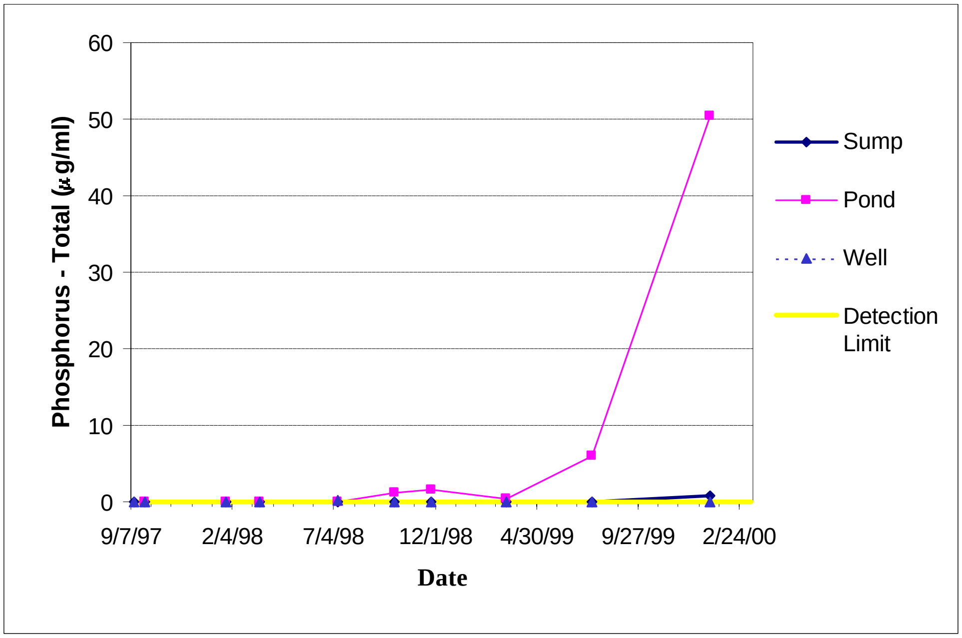


Figure 4.38 Concentration of Total Phosphorous for Sump, Pond, and Well Samples

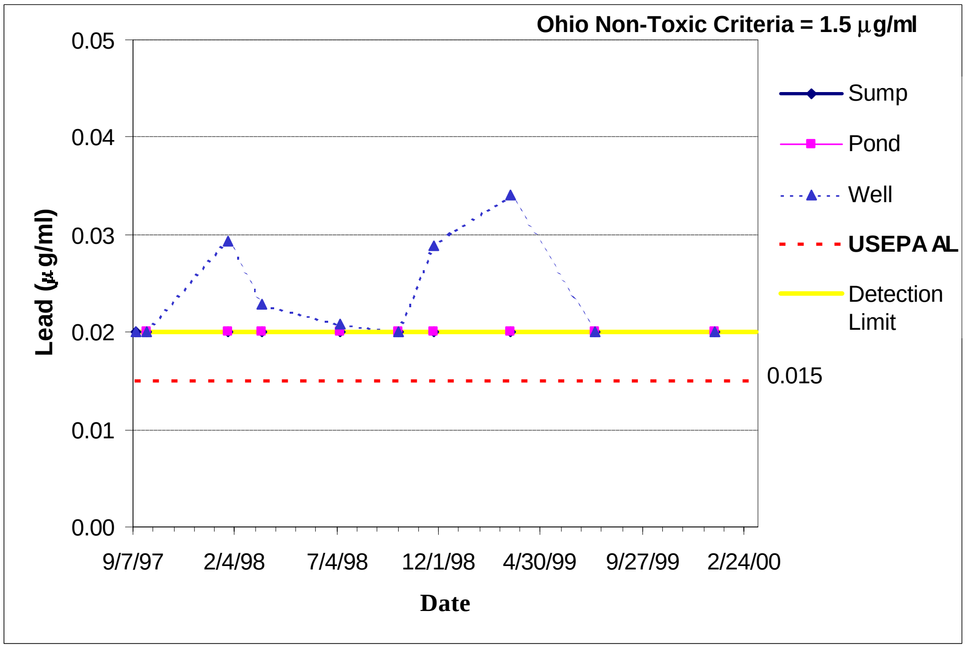


Figure 4.39 Concentration of Lead for Sump, Pond, and Well Samples

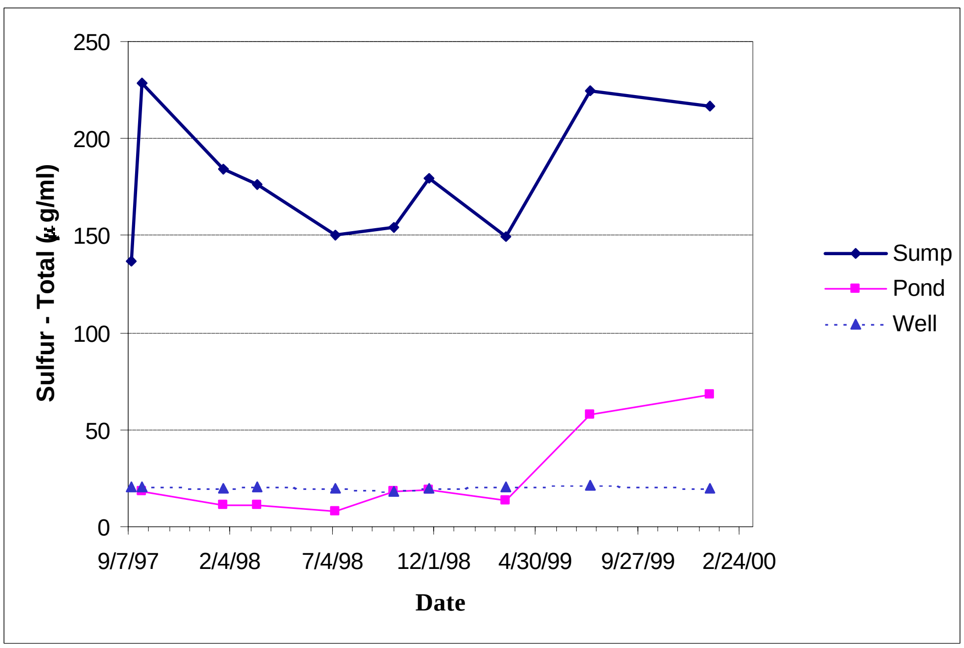


Figure 4.40 Concentration of Total Sulfur for Sump, Pond, and Well Samples

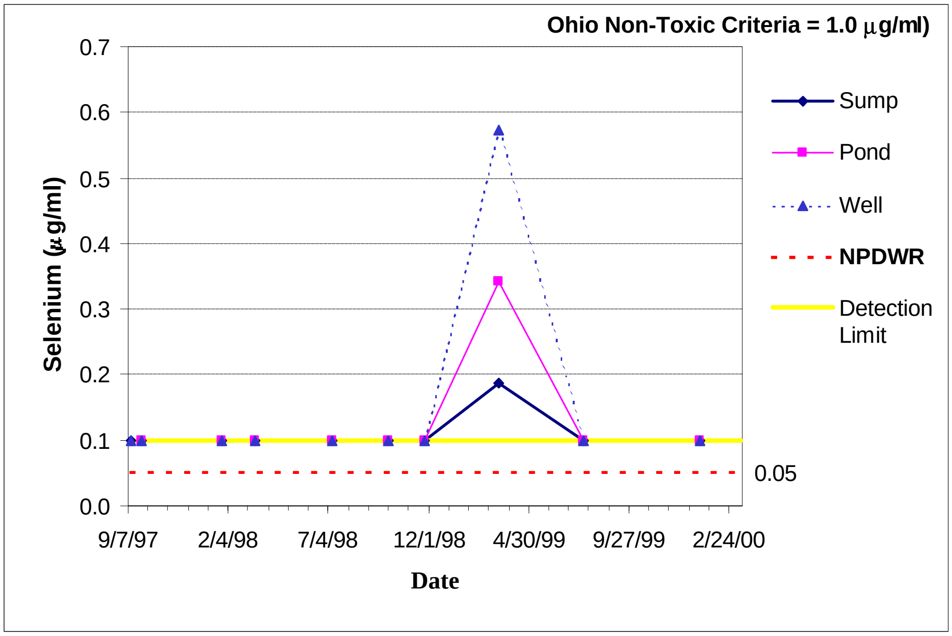


Figure 4.41 Concentration of Selenium for Sump, Pond, and Well Samples

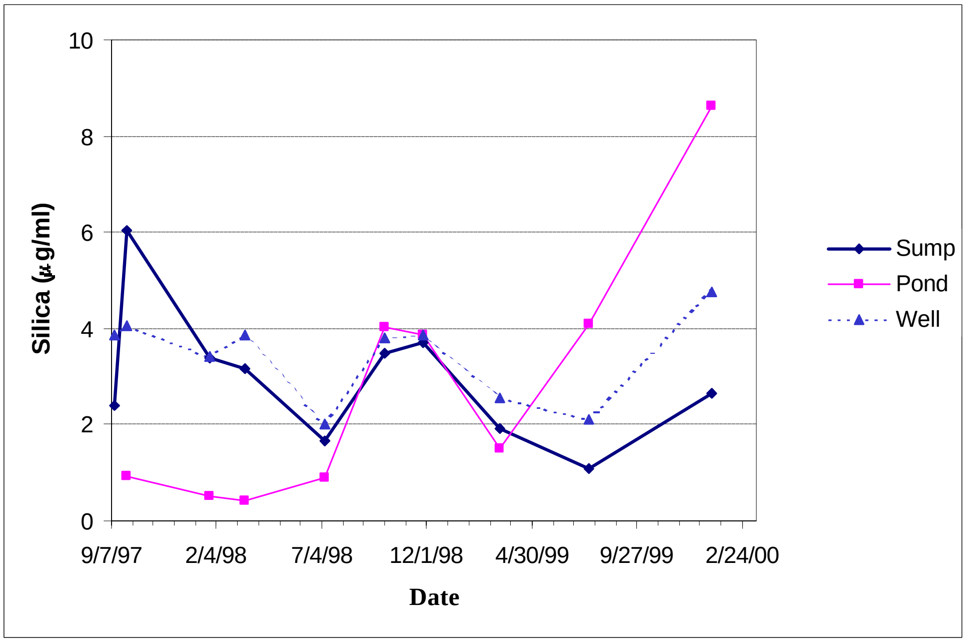


Figure 4.42 Concentration of Silica for Sump, Pond, and Well Samples

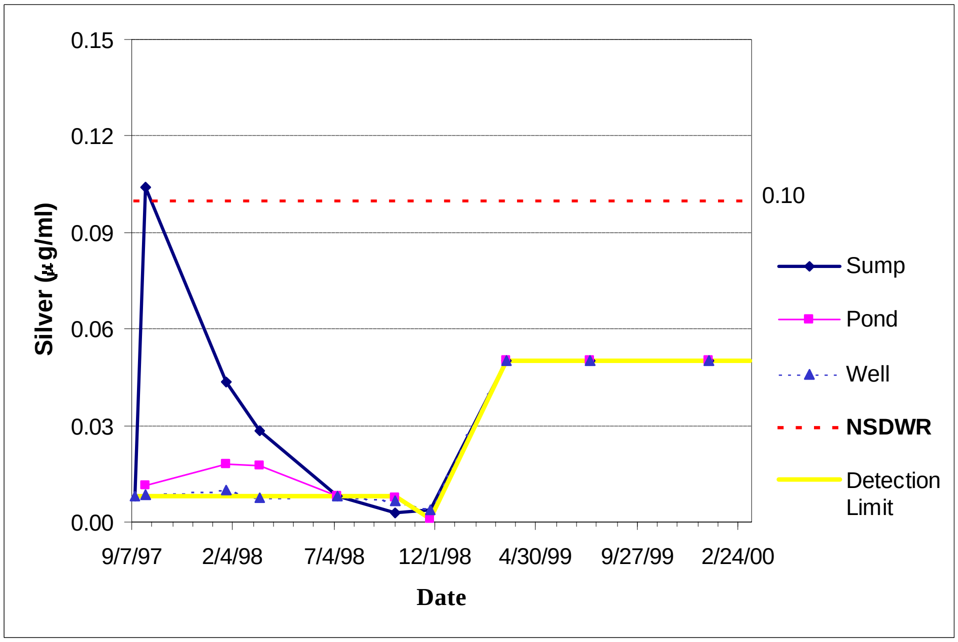


Figure 4.43 Concentration of Silver for Sump, Pond, and Well Samples

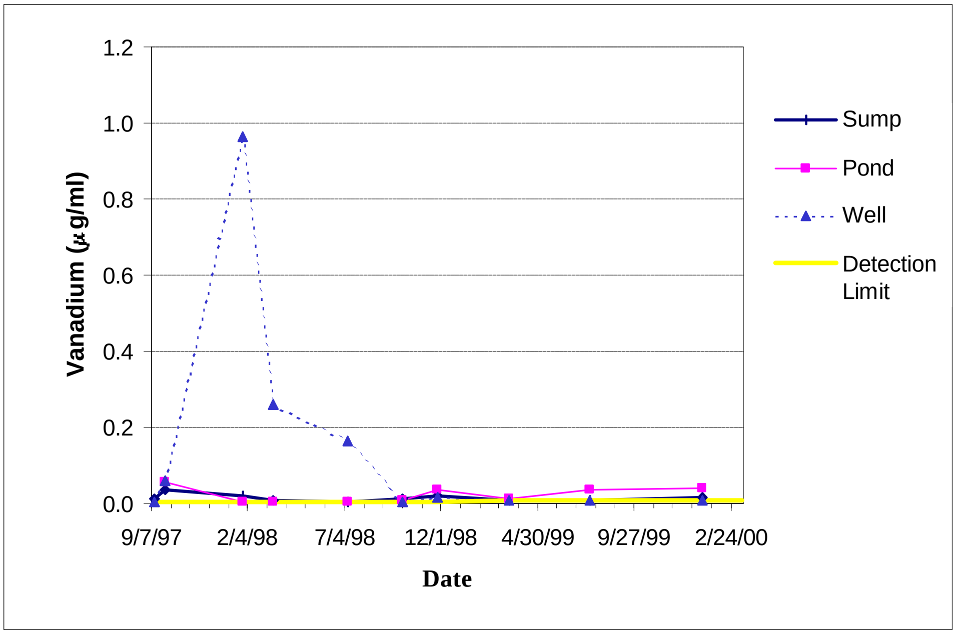


Figure 4.44 Concentration of Vanadium for Sump, Pond, and Well Samples

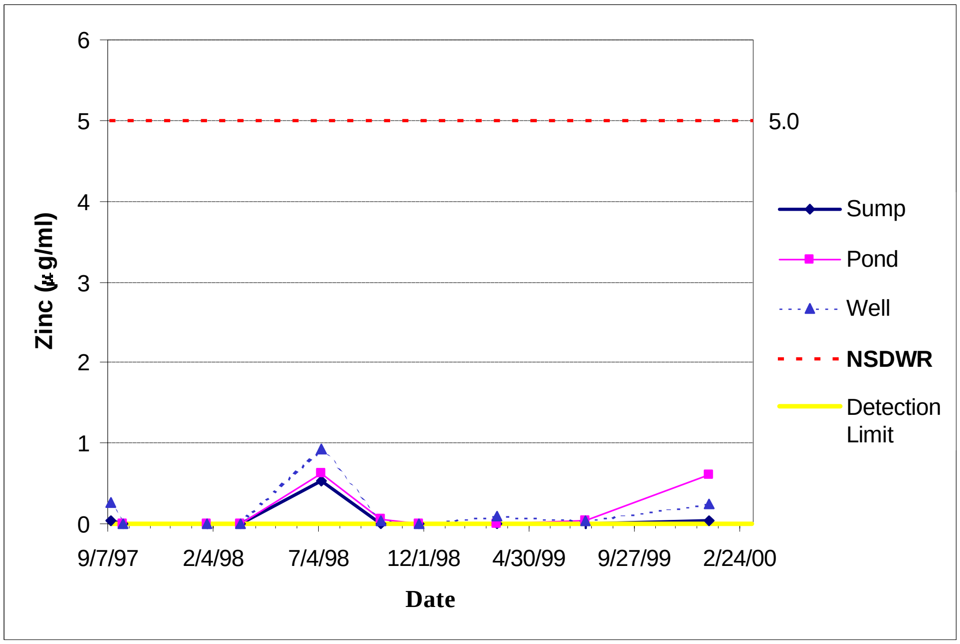


Figure 4.45 Concentration of Zinc for Sump, Pond, and Well Samples

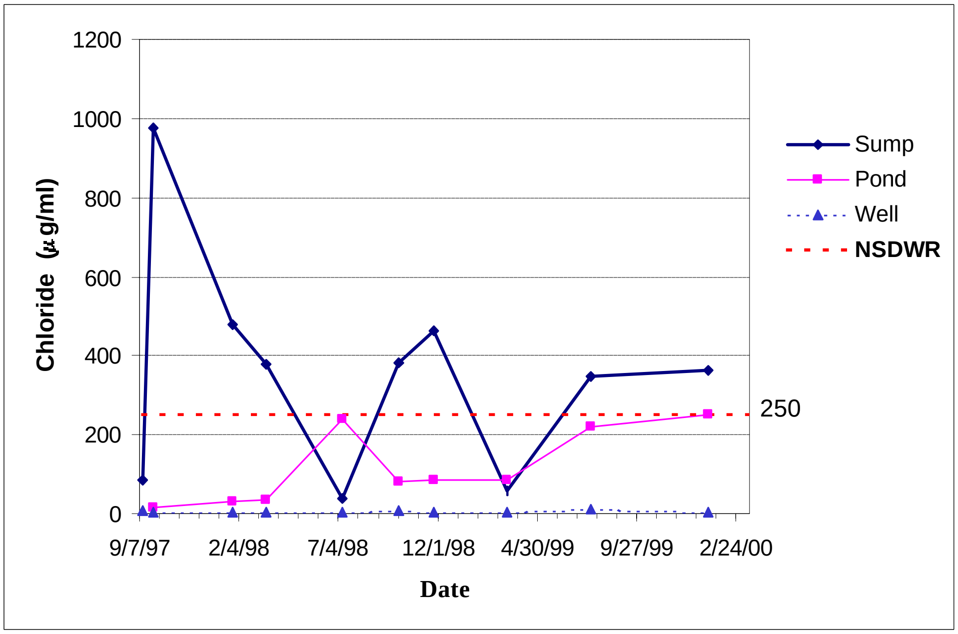


Figure 4.46 Concentration of Chlorides for Sump, Pond, and Well Samples

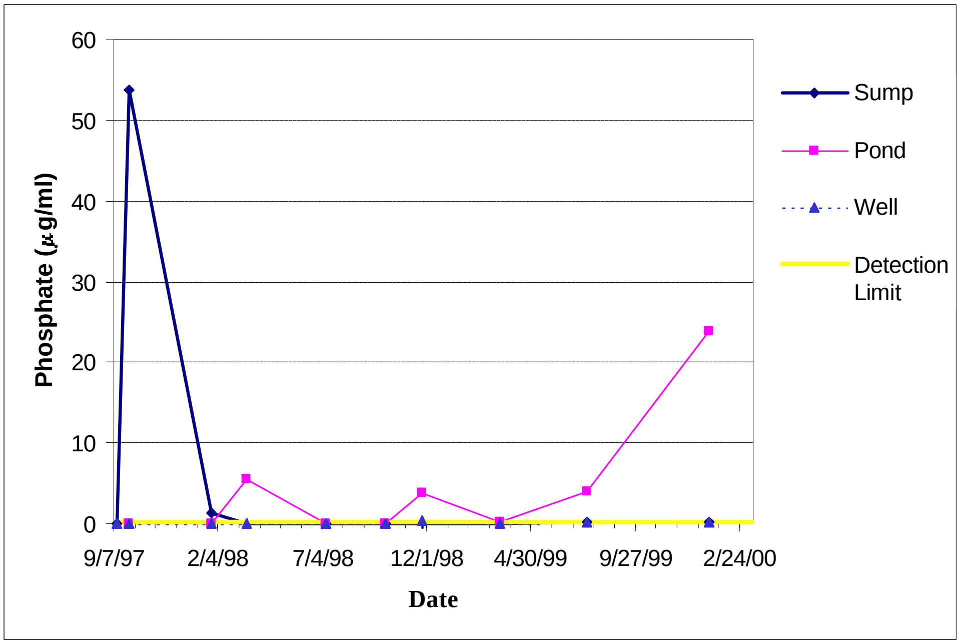


Figure 4.47 Concentration of Phosphates (PO_4) for Sump, Pond, and Well Samples

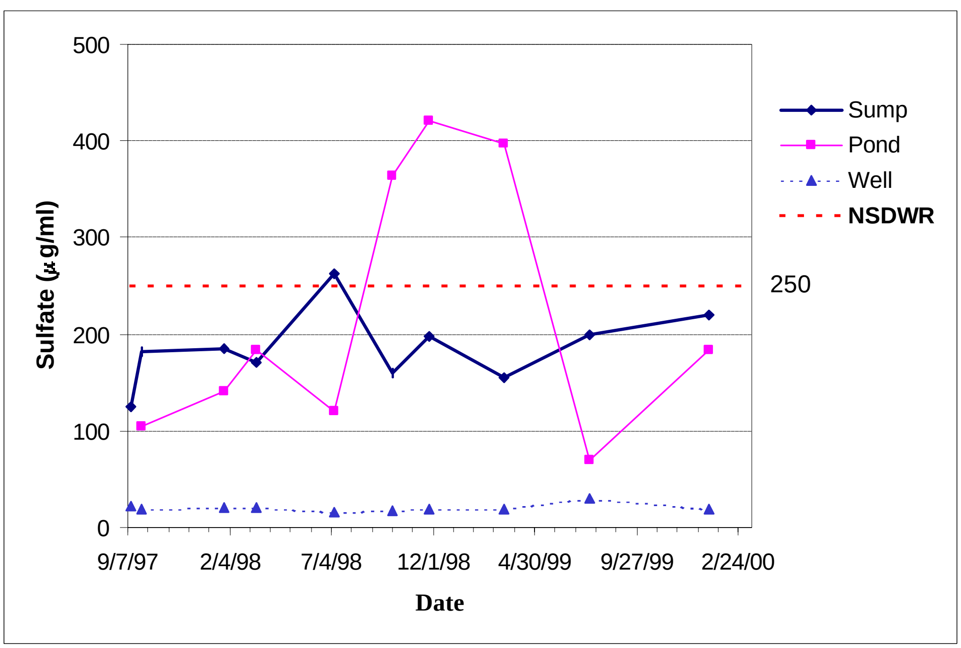


Figure 4.48 Concentration of Sulfates (SO_4) for Sump, Pond, and Well Samples

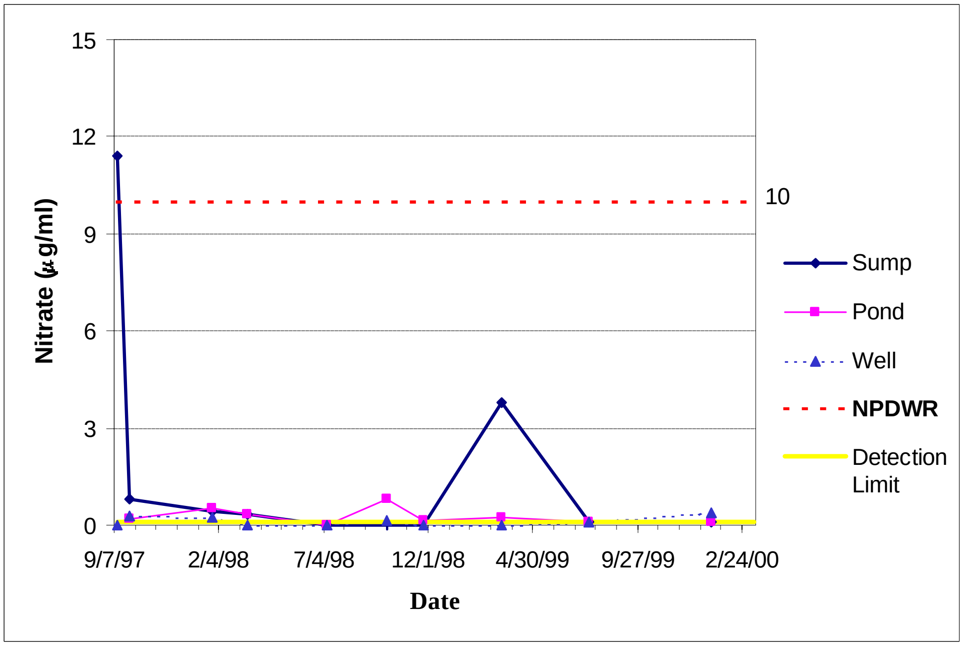


Figure 4.49 Concentration of Nitrates for Sump, Pond, and Well Samples

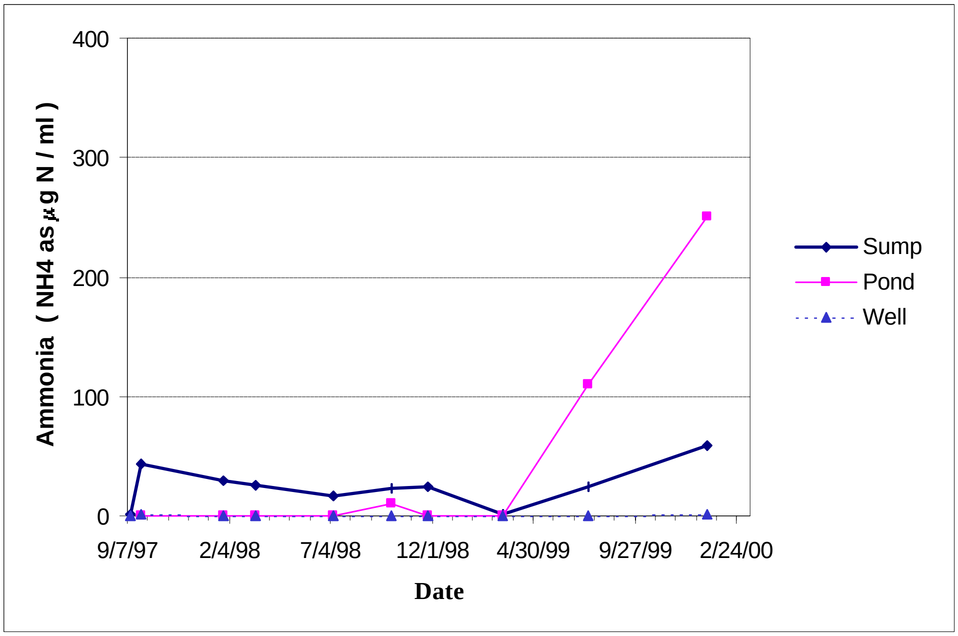


Figure 4.50 Concentration of Ammonia for Sump, Pond, and Well Samples

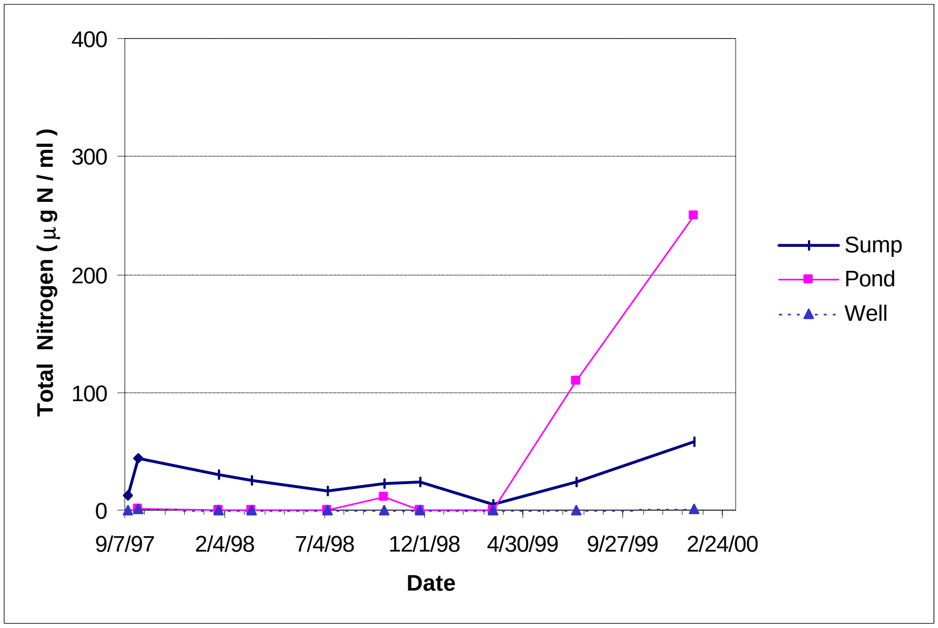


Figure 4.51 Concentration of Total Nitrogen for Sump, Pond, and Well Samples

5 COST ESTIMATES AND PRELIMINARY MARKET EVALUATION

5.1 Introduction

The purpose of this Chapter is to present and compare cost estimates for the creation of wetlands and ponds using FGD and clay liners, and to examine certain macro-features (such as market size, travel time, farm density, etc.) of the potential market for FGD when used as a low permeability liner material. For the cost estimates, a consistent data set published by R. S. Means Company, Inc., was used to allow meaningful comparisons. Typical designs are developed for wetlands and ponds using FGD or clay as a liner material, and a listing of specific construction work items and unit cost data are provided to form a basis for discussion. Modifications, if any, to the work items or unit costs can then be made to adapt them more closely to conditions likely to be found in eastern and southeastern Ohio.

5.2 Cost Estimates

5.2.1 Wetland Creation

5.2.1.1 Design and Construction Process

Figure 5.1 shows a typical cross-section of a wetland to be created through use of a low permeability liner composed of FGD or clay. It is assumed that the created wetland is to be of the "freshwater emergent" type, wherein the depth of water is rather shallow, from 6 to 12 inches. A 6-inch depth is shown in Figure 5.1. It is further assumed that a five-acre (AC) wetland in the shape of a square is to be constructed and that the liner, when made of either material, will be 12 inches thick. An earthen berm 4 ft. high and 35 ft. wide will be constructed with side slopes 2:1. The total footprint of the site is 6.6 acres.

The design and construction process begins with engineering services, site surveying and clearing, and excavation of 24 inches of earth by dozer, with an average 150 ft. haul to clear the site. The liner is then installed by transporting either FGD or clay, spreading this material on-site with a dozer, and compacting in 6-inch lifts with three passes using a riding sheepsfoot roller. Following liner placement (and a suitable time for FGD curing), earth 12 inches thick is placed on the liner for plant rooting. Storm drainage piping, erosion control, and seeding complete the process. For a clay liner, the additional step of clay excavation with a crawler backhoe is required.

5.2.1.2 Work Items and Unit Costs

Tables 5.1 and 5.2 summarize work items, assigned crews, unit costs, quantity of each work item, and estimates of total cost for a five-acre wetland lined with FGD and clay, respectively. The precise make-up of assigned crews is provided in Table 5.3. The cost of additional lime that needs to be added to the FGD material is assumed to be borne by the FGD generator. Cost estimates are provided for a range of alternative haul distances for FGD or clay: 1, 2, 4, 10, 20, and 100 miles round-trip. In addition, the no-cost option for hauling FGD is included to reflect the case wherein no charge is levied by the utility to haul FGD. A location factor is applied to arrive at the final cost estimate. The factor is provided in the Means cost data to account for local cost variations; the factor for Athens, Ohio, is used to most closely represent conditions to be found in eastern and southeastern Ohio. The sub-factor for "installation" was used to adjust for equipment and labor costs, because wetland and pond creation involves only minor cost for materials. The adjustment is large; total costs are reduced by approximately 25 percent compared to the 30-city average upon which the Means cost data is based. The final cost estimate is expressed in January 2000, dollars.

5.2.1.3 Cost Summary

Table 5.4 is a cost comparison of the two methods of wetland creation for a five-acre wetland. If the full cost of hauling FGD or clay to the site (by the same haul distance) are included in the cost analysis, the cost savings in using FGD are $19,754, regardless of haul distance. In this case, all work items are identical in the two options except excavation cost of clay, $25,492. The cost savings of $19,754 is arrived at by multiplying $25,492 by 1.025 to include the cost of engineering, then multiplying by 0.756 to adjust for location. If no cost is assigned to hauling FGD, cost savings increase dramatically with round-trip haul distance for clay.

5.2.1.4 Comparison to Literature Cost Data

Cost of wetland creation as computed herein can be compared to recently developed literature data. King and Bohlen (1994a, b) report the cost of wetland enhancement, restoration, and creation for a wide variety of wetland types. For freshwater emergent wetlands, present worth cost (excluding land cost) can be computed as:

$$\text{Cost}_{1993} = 49742\ A^{0.6167}$$

where cost is in 1993 dollars and A is wetland area, in acres. The exponent on A demonstrates considerable economies of scale for wetland creation. Cost can be adjusted to January 2000 by multiplying by 1.176, based on the Means Historical Cost Index (R.S. Means, 1999, p. 419). This results in

$$\text{Cost}_{2000} = 58497\ A^{0.6167}$$

For a five-acre wetland, cost is estimated to be $157,830, of which post-construction costs (site monitoring and maintenance) comprise 28 percent, on average. Removing this component produces an estimated construction cost of $113,637. This figure is further impacted by the inclusion of projects that undertook wetland planting, a work item not included in current estimates. Although it is not possible to adjust the literature data exactly for the effect of planting, a 10 percent reduction would not be unreasonable, and results in a final literature construction cost estimate of $102,274, quite close to the cost of using FGD with a four-mile round-trip haul, or clay with a one-mile round-trip haul. It is concluded that the cost of wetland creation estimated herein for short haul distances compares reasonably well to literature data.

5.2.2 Water Supply Pond / Wastewater Lagoon

5.2.2.1 Design and Construction Process

Figure 5.2 shows a typical cross-section of a water supply pond or wastewater lagoon to be created through use of a low permeability liner composed of FGD or clay. It is assumed that a 1.0 million gallon (3.07 acre-feet, AF) storage capacity is desired and that the liner, when made of either material, will be 18 inches thick. Further, a depth of nine feet is assumed at the center of the pond, and a 4:1 side slope is selected to minimize the overall footprint of the facility while ensuring ease of construction. For safety, two light fences are recommended, one on top of the berm, and one at the water's edge. The storage capacity of 1.0 million gallons was selected to correspond to the volume installed at the South Charleston, Ohio, facility of the OARDC, which can accommodate about a half-year of onsite swine waste.

Bottom elevation of the pond is raised to reduce excavation volume and to produce a reasonably sized berm. The resulting water surface elevation is two feet above original grade, and a freeboard of three feet is provided. The FGD liner is carried 12 feet horizontally at top of berm. The clay liner is carried only two feet horizontally at top of berm to permit grass seeding on an earthen berm. The footprint of the facility is 288' x 288', or 1.90 acre, and the water surface is 158' x 158', or 0.57 acre.

The design and construction process begins with engineering services, site surveying and clearing, and excavation with a crawler backhoe. The berm is graded with a 200 H. P. dozer.

Pumping of any infiltration water is allowed for. The liner is installed by transporting either FGD or clay in 20 cubic-yard dump-trailers, spreading the material on-site with a dozer, and compacting in 6-inch lifts with three passes using a riding sheepsfoot roller. Storm drainage piping, erosion control, and seeding complete the process. Clay is obtained off-site using a crawler backhoe.

5.2.2.2 Work Items and Unit Costs

Tables 5.5 and 5.6 summarize work items, unit costs, quantity of each work item, and estimates of total cost for the 1.0 million-gallon pond lined with FGD or clay, respectively. The cost of additional lime that needs to be added to the FGD material is assumed to be borne by the FGD generator. Cost estimates are provided for a range of alternative haul distances for FGD or clay; 1, 2, 4, 10, 20, and 100 miles round-trip. In addition, the no-cost option for hauling FGD is included to reflect the case wherein no cost is charged by the utility to haul FGD. A location factor for Athens, Ohio, is applied to arrive at the final cost estimate. The sub-factor for "installation" from the Means cost data was used to adjust for equipment and labor costs, as was done in the cost estimates for wetland creation. The final cost is expressed in January 2000, dollars.

5.2.2.3 Cost Summary for Pond Construction

Table 5.7 is a cost comparison of the two methods of pond construction. If the full cost of hauling FGD to the site is included, the cost savings in using FGD are $3,323 for a 1-mile round-trip but become successively smaller at longer haul distances, and are slightly negative at a 100-mile round-trip. This is caused by the fact that more FGD than clay is used at the site, due to having the perimeter paved with 12 ft. of FGD, but only 2 ft. of clay. With longer haul distances, the initial cost savings from using FGD is gradually consumed. If only 2 ft. of paved perimeter is installed with FGD, the cost differential would remain about $3,323 in favor of FGD, even at longer haul distances. In any case, this represents a rather small cost savings (about 10 percent at a 1-mile round-trip haul, less at longer hauls). If no haul cost for FGD is incurred by the consumer, cost savings are large ($8,396) at a one-mile round-trip and increase steadily as the haul distance increases.

5.2.2.4 Water Supply Pond: Unit Cost of Water

The unit cost of stored water can be calculated if a project life of 20 years and an interest rate of 8 percent are assumed. The procedure is to calculate the equivalent annual cost and divide by the amount of water used each year. Table 5.8 shows unit cost as a function of FGD haul distance if it is assumed that the pond fills and is completely used only once per year. With no cost for hauling FGD, unit cost per thousand gallons is $2.32, or $757 per AF. This is somewhat more than the average retail cost of residential drinking water, and far above the average value of water for irrigation (about $35 per AF in Western states, less in the East). Even with multiple fill-and-draw cycles per year, pond construction for crop irrigation is not viable. However, water used for livestock drinking water in the absence of other sources is a possibility. The value of water when used as a water supply for dairy and beef cattle has not been investigated and needs additional investigations.

5.2.2.5 Comparison to Literature Cost Data

The primary use contemplated for the pond designed herein is for storage of animal manure. Indeed, the construction process as described herein for a lined pond is similar to that for a domestic wastewater stabilization pond, also called an oxidation pond or oxidation lagoon. Theoretically, the cost estimated in this study can therefore be compared to the literature value for a stabilization pond of similar size. As a practical matter, however, domestic wastewater stabilization ponds tend to be larger in surface area and volume than that corresponding to the 1.0 million-gallon design size chosen herein, therefore extrapolation of cost data found in the literature is necessary. Further, only one reference expresses the cost of stabilization ponds in terms of surface area of the pond (Patterson and Banker, 1971). Other references express cost as a function of design flow of the facility, in million gallons per day (U.S. Environmental Protection Agency, 1980) or population equivalents (Butts and Evans, 1970). The latter two cases make it necessary to go through a multi-step calculation involving the assumption of a BOD loading rate for the pond (in pounds per day) and a wastewater flow concentration. Because the design loading rate varies widely among ponds, the resulting calculation can be used only to make rough comparisons. The data of Patterson and Banker (1971) are more reliable, because they express cost directly as a function of pond surface area, eliminating the need to go through a multi-step calculation to determine surface area.

Data for non-aerated ponds are provided by Patterson and Banker (1971, p. 210). However, the smallest pond size reported in their data is 6.0 acres. Extrapolating their line of best fit to a pond surface area of 0.57 acres and converting the resulting cost to January 2000, for Athens, Ohio, using the appropriate Means Historical Cost Index and Location Factor results in a predicted cost of \$28,167. Because stabilization ponds are generally sited in areas of favorable soil conditions (underlying clay), the proper point of comparison would be a pond lined with FGD involving no haul cost. The corresponding cost was estimated to be \$22,809, which is reasonably close considering errors involved in updating cost data and transferring from one location to another. Other possible points of comparison would be the case of a 1-mile round-trip haul cost for FGD, for which the cost was estimated to be \$27,882, or a 1-mile round-trip haul cost for clay, \$31,205, both of which are very close to \$28,167. It should be noted that the data of Patterson and Banker include some items not included in the current cost estimate; an access road, outfall sewer, and fencing. Including such items would make the cost estimated herein closer to the \$28,167 figure.

To test the sensitivity of updated costs to the cost index used, the Engineering News Record (ENR) Construction Cost Index (CCI) was applied to the cost data of Patterson and Banker. This resulted in a predicted cost of \$29,314 at Athens, Ohio, and compares well to the \$28,167 value found using the Means Historical Cost Index. It is concluded that the cost of a water supply pond / wastewater lagoon as estimated herein compares reasonably well to available literature data.

5.3 Preliminary Market Study

5.3.1 Possible Market Size

It is critical to determine the size of possible market for FGD when used in agricultural water supply ponds or waste lagoons. The market in this case is the number of farms within a reasonable haul time or distance from the power plant. This preliminary market study does not include a detailed analysis of clay availability in vicinity of the power plants.

5.3.1.1 Travel Time Contours

Figures 5.3 and 5.4 illustrate travel time contours (isochrones) for 15, 30, and 60 minutes from the Conesville and Gavin power plants, respectively, as determined from field studies. Travel time depends upon the quality of road infrastructure and basic topography of a region. Instate contours for the Conesville power plant are somewhat wider in geographic coverage than the corresponding ones for Gavin, principally because the highway infrastructure near Conesville is of somewhat higher quality. The 60-minute contour for Conesville covers almost an equal number of miles, while that for Gavin covers only about 49 miles.

5.3.1.2 Number of Farms Within Contours

The contour lines can be used to determine the area encompassed by them in each county. Tables 5.9 and 5.10 summarize this data. If it is assumed that farms are evenly distributed throughout a county, farm density for a county (farms per square mile) can be multiplied by county area within a contour to get an estimate of the number of farms in each county that are included. The Census of Agriculture: 1992 (U..S. Department of Commerce, Census of Agriculture, 1994) was used to obtain farm density by county. Calculations carried out in Tables 5.9 and 5.10 show that the density of farms within the 15-minute contour is about the same for the two power plants, but that farm density is much higher at Conesville for the 30 and 60-minute contours. This, coupled with the exclusion of areas outside the state of Ohio, results in a much larger market (number of farms) for the Conesville power plant (23, 64, and 221 percent greater for the 15, 30, and 60 minute contours, respectively).

Figure 5.5 illustrates differences in farm density by county in Ohio. Farms comprise a much higher percent of land area near the Conesville plant than near Gavin. In addition, farms near Conesville tend to have a higher market value of land and buildings, as illustrated in Figure 5.6. By contrast, Figure 5.7 shows that average farm size is about the same in the vicinity of the two plants. Market density, volume, and ability to pay tends to be higher in the vicinity of the Conesville power plant as compared to Gavin.

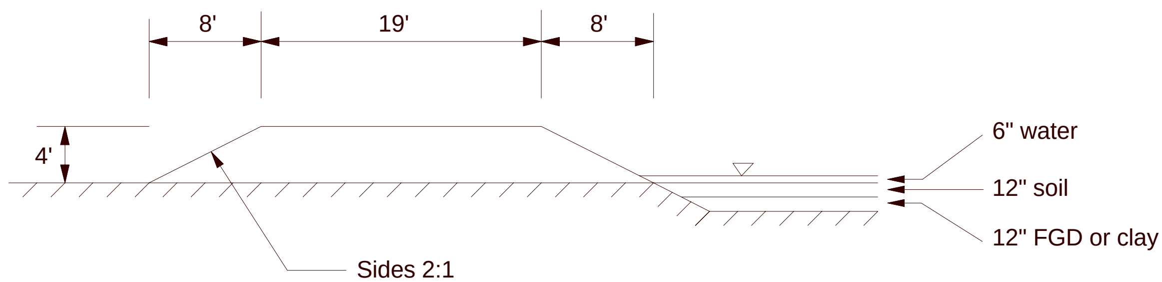


Figure 5.1 Schematic of 5-Acre Wetland Lined With FGD or Clay (not to scale).

Table 5.1 Cost Estimate for 5-Acre Wetland: FGD Liner

Work Item	Crew	Daily Output	Labor-Hours	Unit	Mat	Labor	Equip	Total	Total incl O&P	Qty.	Line Item Total	Notes
Surveying, Conventional Topographic	A-7	3.3	7.273	AC.	16	217		233	360	6.6	2376	
Site Clearing; dozer; trees to 4" diameter	B-11A	8	2	AC.		51	101	152	190	3	570	Assumes only part of site needs treatment
Mobilization	B-34K	6	1.33	Ea.		30.5	153	183.5	215	4	860	2 dozers, 200 HP; 1 tractor; 1 riding sheepsfoot roller; up to 50 miles
Excavating, bulk, dozer; common earth	B-10B	516	0.023	C.Y.		0.62	1.56	2.18	2.67	16,133	43,075	1 dozer, 200 HP; 150 ft. haul; 5 AC site
Compaction, reiding sheepsfoot roller	B-10G	1735	0.007	C.Y.		0.18	0.33	0.51	0.64	8067	5163	6" lifts; 3 passes; embankment berm
*Hauling FGD: 1 mi round-trip	B-34D	325	0.025	C.Y.		0.56	1.73	2.29	2.77	8067	22,346*	20 C.Y. dump trailer; 2.5 loads/hr
*Hauling FGD: 2 mi round-trip	B-34D	260	0.031	C.Y.		0.7	2.17	2.87	3.45	8067	27,831*	20 C.Y. dump trailer; 2 loads/hr
*Hauling FGD: 4 mi round-trip	B-34D	195	0.041	C.Y.		0.94	2.89	3.83	4.61	8067	37,189*	20 C.Y. dump trailer; 1.5 loads/hr
*Hauling FGD: 10 mi round-trip	B-34D	110	0.073	C.Y.		1.66	5.1	6.76	8.2	8067	66,149*	20 C.Y. dump trailer; 0.75 loads/hr
*Hauling FGD: 20 mi round-trip	B-34D	78	0.103	C.Y.		2.34	7.25	9.59	11.55	8067	93,174*	20 C.Y. dump trailer; 0.50 loads/hr
*Hauling FDG: 100 mi round-trip	B-34D	`		mile					2	16,120	125,414*	20 C.Y. dump trailer; price is per loaded mile for hauling beyond 20 miles round-trip
Grading FGD: at dump site, dozer	B-10B	1000	0.012	C.Y.		0.32	0.81	1.13	1.38	8067	11,132	
Compaction of FGD; riding sheepsfoot roller	B-10G	1735	0.007	C.Y.		0.18	0.33	0.51	0.64	8067	5163	6" lifts; 3 passes;
Fill; spread stockpiled earth into wetland	B-10B	1000	0.012	C.Y.		0.32	0.81	1.13	1.38	8067	11,132	1 dozer, 200HP; no compaction
Storm drainage piping; corrugated metal	B-14	190	0.253	L.F.	14.35	5.95	1.07	21.37	26	140	3640	(4) 18" dia, 16 gauge, 35' length (2) upstream, (2) downstream
Erosion control; paper biodegradable mesh	B-1	2500	0.01	S.Y.	0.07	0.22		0.29	0.43	8250	3548	Entire berm
Seed berm; bluegrass, tractor spreader	B-66	52	0.154	MSF	14	4.25	3.6	21.85	26	75	1950	4 lbs/MSF (MSF=1000 sq. ft.)
Subtotals:												
Without FGD haul cost											88,609	
1 mi round-trip											110,955	
2 mi round-trip											116,440	
4 mi round-trip											125,798	
10 mi round-trip											154,758	
20 mi round-trip											181,783	
100 mi round-trip											214,023	
Engineering fees; landscaping/site development												at 2.5 percent
Without FGD haul cost											90,824	
1 mi round-trip											113,770	
2 mi round-trip											119,351	
4 mi round-trip											128,943	
10 mi round-trip											158,627	
20 mi round-trip											186,328	
100 mi round-trip											219,374	
Location factor, Athens, Ohio, multiply by 0.756												for installation (labor and equipment) only
Total Cost												
Without FGD haul cost											68,663	
1 mi round-trip											86,010	
2 mi round-trip											90,229	
4 mi round-trip											97,481	
10 mi round-trip											119,922	
20 mi round-trip											140,864	
100 mi round-trip											165,846	

*Alternative haul cost figures

Table 5.2 Cost Estimate for 5-Acre Wetland: Clay Liner

Work Item	Crew	Daily Output	Labor-Hours	Unit	Mat	Labor	Equip	Total	Total Incl O&P	Qty.	Line Item Total	Notes
Surveying, Conventional Topographic	A-7	3.3	7.273	AC.	16	217		233	360	6.6	2376	
Site clearing; with dozer; trees to 4" diameter	B-11A	8	2	AC.		51	101	152	190	3	570	Assumes only part of site needs treatment
Mobilization	B-34K	6	1.33	Ea.		30.5	153	183.5	215	4	860	2 dozers, 200 HP; 1 tractor; 1 riding sheepsfoot roller; up to 50 miles
Excavating, bulk, dozer, common earth	B-10B	516	0.023	C.Y.		0.62	1.56	2.18	2.67	16,133	43,075	1 dozer, 200 HP; 150 ft. haul; 5 AC site
Compaction; riding sheepsfoot roller	B-10G	1735	0.007	C.Y.		0.18	0.33	0.51	0.64	8067	5163	6" lifts, 3 passes for embankment berm
Clay Excavation; off-site, crawler backhoe	B-12C	1040	0.15	C.Y.			0.51	2.58	3.16	8067	25,492	2 C.Y. capacity; 130 C.Y./hr; includes additional 15% for loading and 60% for heavy clay
*Hauling Clay: 1 mile round-trip	B-34D	325	0.25	C.Y.		0.56	1.73	2.29	2.77	8067	22,346*	20 C.Y. dump trailer; 2.5 loads/hr
*Hauling Clay: 2 mile round-trip	B-34D	260	0.031	C.Y.		0.7	2.17	2.87	3.45	8067	27,831*	20 C.Y. dump trailer; 2 loads/hr
*Hauling Clay: 4 mile round-trip	B-34D	195	0.041	C.Y.		0.94	2.89	3.83	4.61	8067	37,189*	20 C.Y. dump trailer; 1.5 loads/hr
*Hauling Clay: 10 mile round-trip	B-34D	110	0.073	C.Y.		1.66	5.1	6.76	8.2	8067	66,149*	20 C.Y. dump trailer; 0.75 loads/hr
*Hauling Clay: 20 mile round-trip	B-34D	78	0.103	C.Y.		2.34	7.25	9.59	11.55	8067	93,174*	20 C.Y. dump trailer; 0.50 loads/hr
*Hauling Clay: 100 mile round-trip	B-34D	`		mile					2	16,120	125,414*	20 C.Y. dump trailer; price is per loaded mile for hauling beyond 20 miles round-trip
Grading Clay; at-site, dozer	B-10B	1000	0.012	C.Y.		0.32	0.81	1.13	1.38	8067	11,132	
Compaction of Clay; riding sheepsfoot roller	B-10G	1735	0.007	C.Y.		0.18	0.33	0.51	0.64	8067	5163	6" lifts; 3 passes
Fill; spread stockpiled earth into wetland	B-10B	1000	0.012	C.Y.		0.32	0.81	1.13	1.38	8067	11,132	1 dozer, 200HP; no compaction
Storm Drainage Piping; corrugated metal	B-14	190	0.253	L.F.	14.35	5.95	1.07	21.37	26	140	3640	(4) 18" diameter, 16 gauge, 35' length, (2) upstream, (2) downstream
Erosion Control; paper biodegradable mesh	B-1	2500	0.01	S.Y.	0.07	0.22		0.29	0.43	8250	3548	Entire berm
Seed berm; bluegrass, tractor spreader	B-66	52	0.154	MSF	14	4.25	3.6	21.85	26	75	1950	4 lbs/MSF (MSF=thousand sq. ft.)
Subtotals:												
1 mile round-trip											136,447	
2 mile round-trip											141,932	
4 mile round-trip											151,290	
10 mile round-trip											180,250	
20 mile round-trip											207,275	
100 mile round-trip											239,515	
Engineering Fees; landscaping/site development												at 2.5 percent
1 mile round-trip											139,858	
2 mile round-trip											145,480	
4 mile round-trip											155,072	
10 mile round-trip											184,756	
20 mile round-trip											212,457	
100 mile round-trip											245,503	
Location factor: Athens, Ohio, multiply by 0.756												for installation (labor and equipment) only
Total Cost												
1 mile round-trip											105,733	
2 mile round-trip											109,983	
4 mile round-trip											117,234	
10 mile round-trip											139,676	
20 mile round-trip											160,617	
100 mile round-trip											185,600	

*Alternative haul cost figures

Table 5.3 Construction Crew Components

Crew #	Components
A-7	1 chief of party; 1 instrument man; 1 rodman/chainman
B-1	1 labor foreman (outside); 2 laborers
B-10B	1 equipment operator (med); 0.5 laborer; 1 dozer, 200 HP
B-10G	1 equipment operator (med); 0.5 laborer; 1 sheepsfoot roller, 130 HP
B-10H	1 equipment operator (med); 0.5 laborer; 1 diaphragm water pump, 2"; 1-20' suction hose, 2"; 2-50' discharge hoses, 2"
B-11A	1 equipment operator (med); 1 laborer; 1 dozer, 200 HP
B-12C	1 equipment operator (crane); 1 equipment operator, oiler; 1 hyd. excavator, 2 C.Y.
B-14	1 labor foreman (outside); 4 laborers; 1 equipment operator (light); 1 backhoe loader, 48 HP
B-34D	1 truck driver (heavy); 1 truck tractor, 40 ton; 1 dump trailer, 20 C.Y.
B-34K	1 truck driver (heavy); 1 truck tractor, 240 HP; 1 low bed trailer
B-66	1 equipment operator (light); 1 backhoe ldr w/attachment

Table 5.4 Cost Comparison of Wetland Creation Using an FGD or Clay Liner

Haul Assumption	Cost of Created Wetland Using		FGD Cost Savings	
	FGD	Clay	without haul cost for FGD	with haul cost for FGD
without haul cost	$68,663	---	---	---
1 mile round-trip	86,010	$105,733	$37,070	$19,723
2 mile round-trip	90,229	109,983	41,320	19,754
4 mile round-trip	97,481	117,234	48,571	19,753
10 mile round-trip	119,922	139,676	71,013	19,754
20 mile round-trip	140,864	160,617	91,954	19,753
100 mile round-trip	165,846	185,600	116,937	19,754

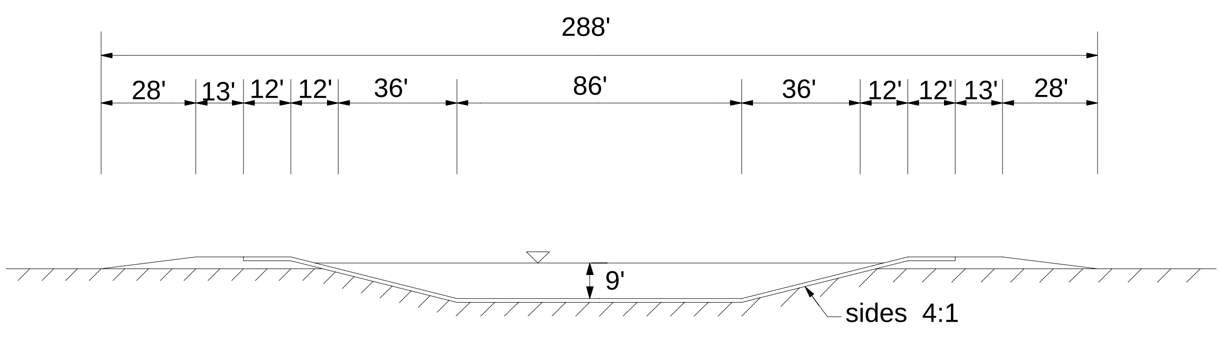


Figure 5.2 Schematic of Million Gallon Pond Lined With FGD or Clay (not to scale)

Table 5.5 Cost Estimate for Million Gallon Pond: FGD Liner

Work Item	Crew	Daily Output	Labor-Hours	Unit	Mat	Labor	Equip	Total	Total incl O&P	Qty.	Line Item Total	Notes
Surveying; conventional topographic	A-7	3.3	7.273	AC.	16	217		233	360	1.9	684	
Site Clearing; with dozer; trees to 4" diameter	B-11A	8	2	AC.		51	101	152	190	1	190	assumes only half the site needs treatment
Mobilization	B-34K	6	1.33	Ea.		30.5	153	183.5	215	4	860	2 dozers, 200 HP; 1 tractor; 1 riding sheepsfoot roller; 1 crawler backhoe
Excavating; crawler backhoe	B-12C	1040	0.015	C.Y.		0.42	0.98	1.4	1.72	4979	8564	common earth; 2.0 C.Y. capacity; 130 C.Y./hr
Dewatering; pumping	B-10H	4	3	day		80	11.65	91.65	136	5	680	2" diaphragm pump, used 8 hrs/day, includes hoses
Grading Berm; dozer	B-10B	1000	0.012	C.Y.		0.32	0.81	1.13	1.38	4979	6871	
Compaction of Berm; riding sheepsfoot roller	B-10G	1735	0.007	C.Y.		0.18	0.33	0.51	0.64	4979	3187	6" lifts, 3 passes
*Hauling FGD: 1 mile round-trip	B-34D	325	0.025	C.Y.		0.56	1.73	2.29	2.77	2363	6546*	20 C.Y. dump trailer; 2.5 loads/hr
*Hauling FGD: 2 mile round-trip	B-34D	260	0.031	C.Y.		0.7	2.17	2.87	3.45	2363	8152*	20 C.Y. dump trailer; 2 loads/hr
*Hauling FGD; 4 mile round-trip	B-34D	195	0.041	C.Y.		0.94	2.89	3.83	4.61	2363	10,893*	20 C.Y. dump trailer; 1.5 loads/hr
*Hauling FGD; 10 mile round-trip	B-34D	110	0.073	C.Y.		1.66	5.1	6.76	8.2	2363	19,377*	20 C.Y. dump trailer; 0.75 loads/hr
*Hauling FGD; 20 mile round-trip	B-34D	78	0.103	C.Y.		2.34	7.25	9.59	11.55	2363	27,293*	20 C.Y. dump trailer; 0.50 loads/hr
*Hauling FGD; 100 mile round-trip	B-34D	`		mile					2	4726	36,745*	20 C.Y. dump trailer; price is per loaded mile for hauling beyond 20 miles round-trip
Grading FGD; dozer	B-10B	1000	0.012	C.Y.		0.32	0.81	1.13	1.38	2363	3261	
Compaction of FGD; riding sheepsfoot roller	B-10G	1735	0.007	C.Y.		0.18	0.33	0.51	0.64	2363	1512	6" lifts, 3 passes
Storm Drainage Piping; corrugated metal	B-14	190	0.253	L.F.	14.35	5.95	1.07	21.37	26	50	1300	(1) 18" dia, 16 gauge
Erosion Control; paper biodegradable mesh	B-1	2500	0.01	S.Y.	0.07	0.22		0.29	0.43	3505	1507	on exposed berm
Seed Berm; bluegrass, tractor spreader	B-66	52	0.154	MSF	14	4.25	3.6	21.85	26	31.5	819	on exposed berm; 4 lbs/MSF (MSF=1000 sq. ft.)
Subtotals:												
Without FGD haul cost											29,435	
1 mile round-trip											35,981	
2 mile round-trip											37,587	
4 mile round-trip											40,328	
10 mile round-trip											48,812	
20 mile round-trip											56,728	
100 mile round-trip											66,180	
Engineering Fees; landscaping/site development												at 2.5 percent
Without FGD haul cost											30,171	
1 mile round-trip											36,881	
2 mile round-trip											38,527	
4 mile round-trip											41,336	
10 mile round-trip											50,032	
20 mile round-trip											58,146	
100 mile round-trip											67,835	
Location Factor: Athens, Ohio, multiply by 0.756												
Without FGD haul costs											22,809	
1 mile round-trip											27,882	
2 mile round-trip											29,126	
4 mile round-trip											31,250	
10 mile round-trip											37,824	
20 mile round-trip											43,958	
100 mile round-trip											51,283	

*Alternative haul cost figures

Table 5.6 Cost Estimate for Million Gallon Pond: Clay Liner

Work Item	Crew	Daily Output	Labor-Hours	Unit	Mat	Labor	Equip	Total	Total Incl O&P	Qty.	Line Item Total	Notes
Surveying; conventional topographic	A-7	3.3	7.273	AC.	16	217		233	360	1.9	684	
Site Clearing; with dozer; trees to 4" diameter	B-11A	8	2	AC.		51	101	152	190	1	190	assumes only half the site needs treatment
Mobilization	B-34K	6	1.33	Ea.		30.5	153	183.5	215	4	860	1 dozer, 200 HP; 1 tractor; 1 riding sheepsfoot roller; 1 crawler backhoe
Excavating; crawler backhoe	B-12C	1040	0.015	C.Y.		0.42	0.98	1.4	1.72	4979	8,564	common earth; 2.0 C.Y. capacity; 130 C.Y./hr
Dewatering; pumping	B-10H	4	3	day		80	11.65	91.65	136	5	680	2" diaphragm pump, used 8 hrs/day, includes hoses
Grading Berm; dozer	B-10B	1000	0.012	C.Y.		0.32	0.81	1.13	1.38	4979	6,871	
Compaction of Berm; riding sheepsfoot roller	B-10G	1735	0.007	C.Y.		0.18	0.33	0.51	0.64	4979	3187	6" lifts, 3 passes
Clay Excavation; off-site, crawler backhoe	B-12C	1040	0.015	C.Y.				2.58	3.16	1946	6,149	2 C.Y. capacity; 130 C.Y./hr; includes additional 15% for loading and 60% for heavy clay
*Hauling Clay: 1 mile round-trip	B-34D	325	0.25	C.Y.		0.56	1.73	2.29	2.77	1946	5390*	20 C.Y. dump trailer; 2.5 loads/hr
*Hauling Clay: 2 mile round-trip	B-34D	260	0.031	C.Y.		0.7	2.17	2.87	3.45	1946	6714*	20 C.Y. dump trailer; 2 loads/hr
*Hauling Clay: 4 mile round-trip	B-34D	195	0.041	C.Y.		0.94	2.89	3.83	4.61	1946	8971*	20 C.Y. dump trailer, 1.5 loads/hr
*Hauling Clay: 10 mile round-trip	B-34D	110	0.073	C.Y.		1.66	5.1	6.76	8.2	1946	15,957*	20 C.Y. dump trailer; 0.75 loads/hr
*Hauling Clay: 20 mile round-trip	B-34D	78	0.103	C.Y.		2.34	7.25	9.59	11.55	1946	22,476*	20 C.Y. dump trailer; 0.50 loads/hr
*Hauling Clay: 100 mile round-trip	B-34D	`		mile					2	3892	30,260*	20 C.Y. dump trailer; price is per loaded mile for hauling beyond 20 miles round-trip
Grading Clay; dozer	B-10B	1000	0.012	C.Y.		0.32	0.81	1.13	1.38	1946	2,685	
Compaction of Clay; riding sheepsfoot roller	B-10G	1735	0.007	C.Y.		0.18	0.33	0.51	0.64	1946	1245	6" lifts, 3 passes
Storm Drainage Piping; corrugated metal	B-14	190	0.253	L.F.	14.35	5.95	1.07	21.37	26	50	1300	(1) 18" dia, 16 gauge
Erosion Control; paper biodegradable mesh	B-1	2500	0.01	S.Y.	0.07	0.22		0.29	0.43	3714	1597	treat entire berm
Seed Berm; bluegrass, tractor spreader	B-66	52	0.154	MSF	14	4.25	3.6	21.85	26	33.4	868	treat entire berm
Subtotals:												
1 mile round-trip											40,270	
2 mile round-trip											41,594	
4 mile round-trip											43,851	
10 mile round-trip											50,837	
20 mile round-trip											57,356	
100 mile round-trip											65,140	
Engineering Fees; landscaping/site development												at 2.5 percent
1 mile round-trip											41,277	
2 mile round-trip											42,634	
4 mile round-trip											44,947	
10 mile round-trip											52,107	
20 mile round-trip											58,790	
100 mile round-trip											66,769	
Location Factor: Athens, Ohio, multiply by 0.756												for installation (labor and equipment) only
1 mile round-trip											31,205	
2 mile round-trip											32,231	
4 mile round-trip											33,980	
10 mile round-trip											39,393	
20 mile round-trip											44,445	
100 mile round-trip											50,477	

*Alternative haul cost figures

Table 5.7 Cost Comparison of Pond Construction Using an FGD or Clay Liner

Haul Assumption	**Cost of Construction Using**		**FGD Cost Savings**	
	FGD	**Clay**	**without haul cost for FGD**	**with haul cost for FGD**
without haul cost	$22,809	---	---	---
1 mile round-trip	27,882	$31,205	$8396	$3323
2 mile round-trip	29,126	32,231	9422	3105
4 mile round-trip	31,250	33,980	11,171	2730
10 mile round-trip	37,824	39,393	16,584	1569
20 mile round-trip	43,958	44,445	21,636	487
100 mile round-trip	51,283	50,477	27,668	(806)

( ) = negative savings

Table 5.8 Unit Cost of Water from Pond Constructed with FGD Liner

Haul Condition	**Construction Cost**	**Annual Cost***	**Single Use Per Year**	
			Cost per 1000 gallons	**Cost per Acre-Foot**
w/o Haul Cost	$22,809	$2323	$2.32	$757
1 mile round-trip	27,882	2840	2.84	925
2 mile round-trip	29,126	2967	2.97	966
4 mile round-trip	31,250	3183	3.18	1037
10 mile round-trip	37,824	3852	3.85	1255
20 mile round-trip	43,958	4477	4.48	1458
100 mile round-trip	51,283	5223	5.22	1701

* 8 percent interest rate, 20-year life.

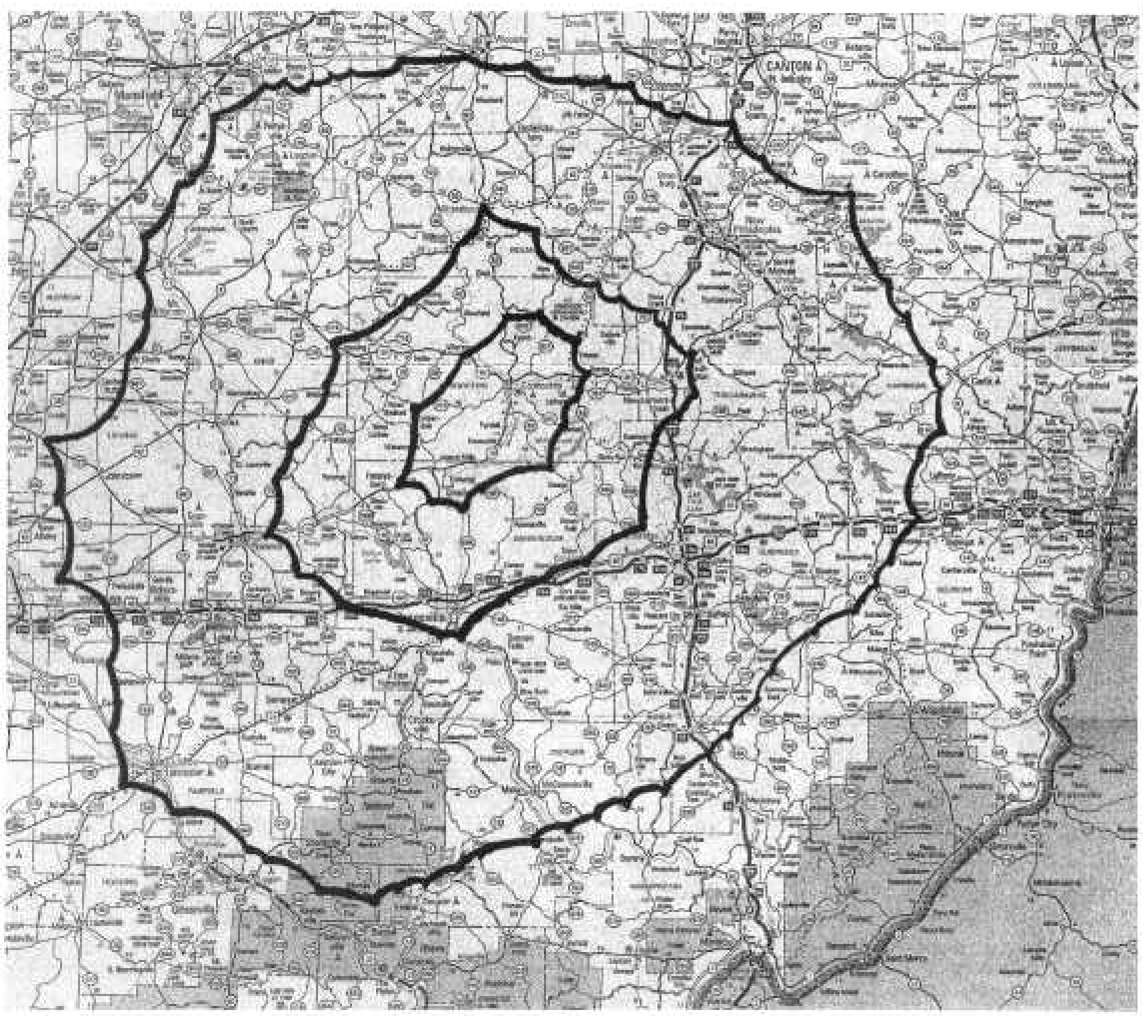


Figure 5.3 Travel-Time Contours from Conesville Power Plant (15, 30, 60 minutes)

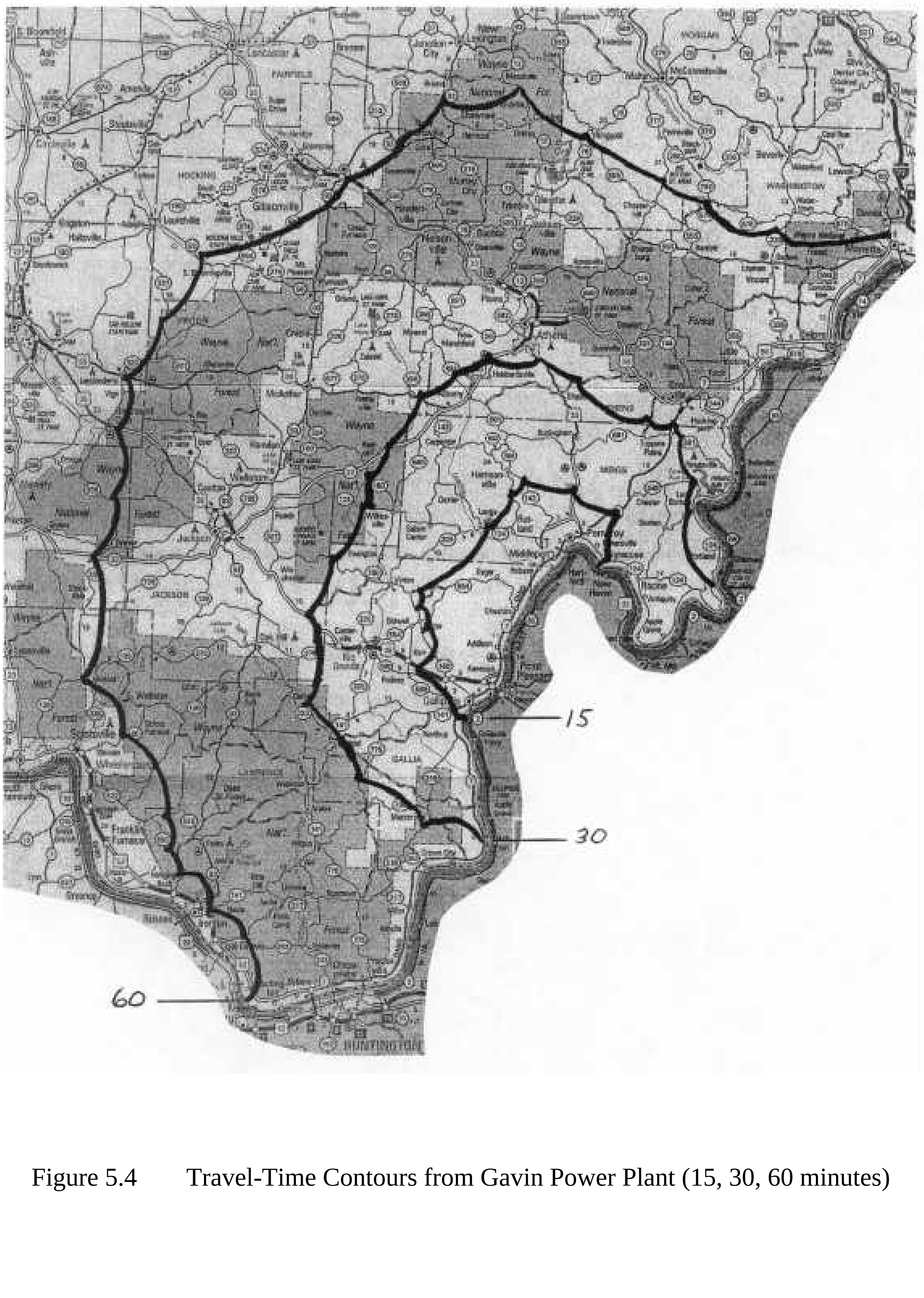


Figure 5.4 Travel-Time Contours from Gavin Power Plant (15, 30, 60 minutes)

Table 5.9 Number of Farms Within Various Haul-Time Contours: Conesville

15-MIN CONTOUR

County	Area(mi2)	Farms/mi2	Farms
Coshocton	149.78	1.44	215.68
Muskingum	38.32	1.58	60.55
	188.10	1.51	276
	Total	Avg.	Total

30-MIN CONTOUR (includes 15-min contour)

County	Area(mi2)	Farms/mi2	Farms
Coshocton	513.77	1.44	739.83
Guernsey	53.99	1.47	79.37
Holmes	27.87	3.41	95.06
Knox	19.16	2.09	40.04
Licking	94.05	1.83	172.11
Muskingum	330.9	1.58	522.82
Tuscarawas	41.8	1.62	67.72
	1081.54	1.92	1717
	Total	Avg.	Total

60-MIN CONTOUR (includes 30 min contour)

County	Area(mi2)	Farms/mi2	Farms
Ashland	85.34	2.25	192.02
Belmont	66.18	1.12	74.12
Carroll	43.54	1.75	76.20
Coshocton	560.79	1.44	807.54
Delaware	10.45	1.55	16.20
Fairfield	212.47	2.09	444.06
Franklin	6.97	0.9	6.27
Guernsey	491.13	1.47	721.96
Harrison	205.51	0.97	199.34
Hocking	12.19	0.84	10.24
Holmes	414.5	3.41	1413.45
Knox	468.49	2.09	979.14
Licking	639.16	1.83	1169.66
Morgan	235.11	1.34	315.05
Morrow	3.48	1.84	6.40
Muskingum	664.28	1.58	1049.56
Noble	146.29	1.38	201.88
Perry	384.89	1.41	542.69
Richland	71.4	1.86	132.80
Stark	24.38	1.94	47.30
Tuscarawas	562.53	1.62	913.55
Wayne	142.81	2.85	407.01
	5451.89	1.71	9726
	Total	Avg.	Total

Table 5.10 Number of Farms Within Various Haul-Time Contours: Gavin

15-MIN CONTOUR

County	Area (mi2)	Farms/mi2	Farms
Gallia	101.01	1.7	171.72
Meigs	45.28	1.15	52.07
	146.29	1.43	224
	Total	Avg.	Total

30-MIN CONTOUR (includes 15-min contour)

County	Area (mi2)	Farms/mi2	Farms
Athens	55.73	0.99	55.17
Gallia	329.16	1.7	559.57
Jackson	6.97	0.92	6.41
Meigs	365.73	1.15	420.59
Vinton	17.42	0.5	8.71
	775.01	1.05	1050
	Total	Avg.	Total

60-MIN CONTOUR (includes 30-min contour)

County	Area (mi2)	Farms/mi2	Farms
Athens	55.73	0.99	55.17
Gallia	459.78	1.7	781.63
Hocking	184.61	0.84	155.07
Jackson	424.95	0.92	390.95
Lawrence	397.08	1.12	444.73
Meigs	416.24	1.15	478.68
Morgan	55.73	1.34	74.68
Perry	36.57	1.41	51.56
Pike	24.38	0.86	20.97
Ross	10.45	1.18	12.33
Scioto	87.08	0.99	86.21
Vinton	402.31	0.5	201.16
Washington	208.99	1.36	284.23
	2763.9	1.10	3037
	Total	Avg.	Total

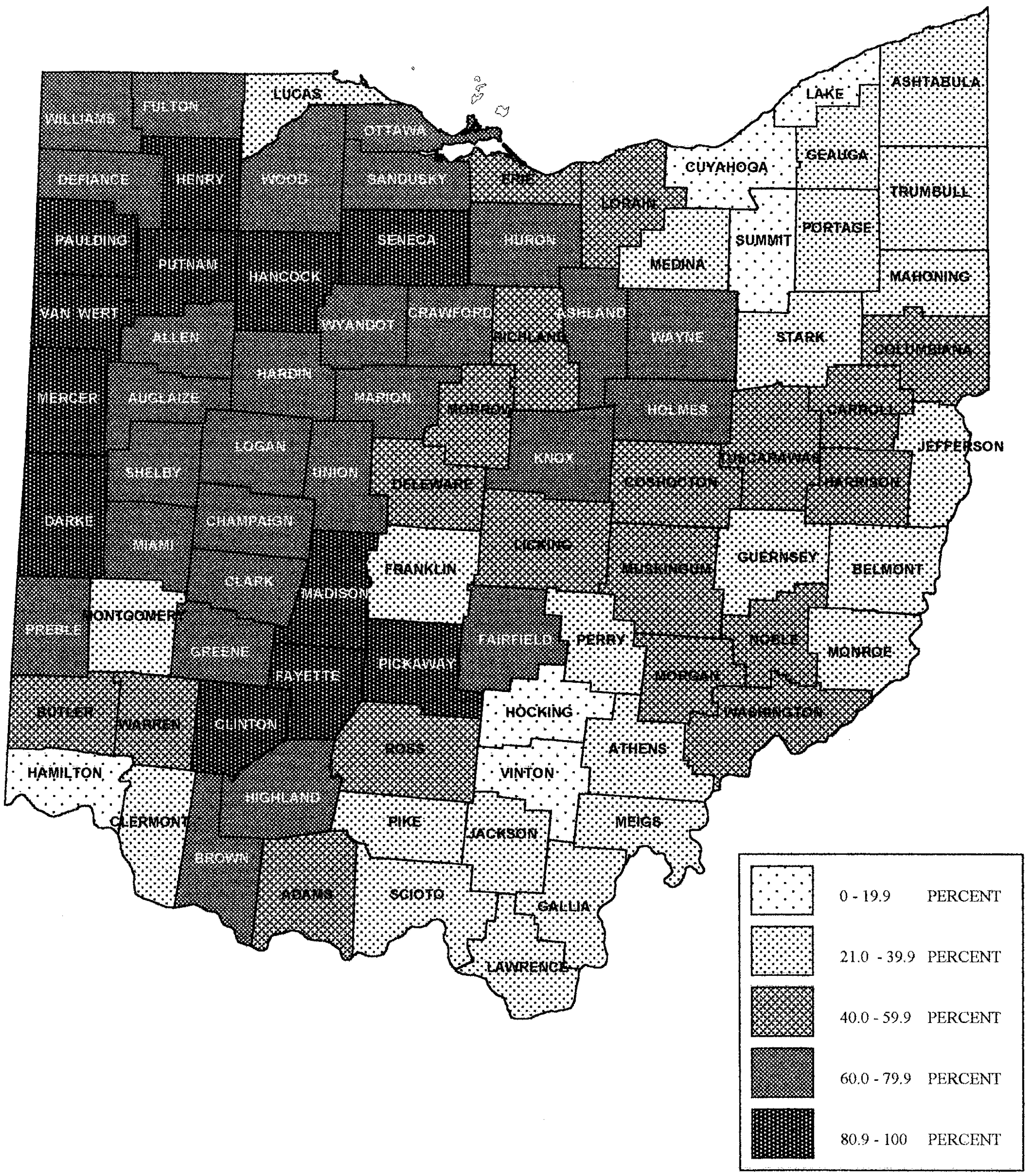


Figure 5.5 Approximate Land Area Proportion in Farms in 1992

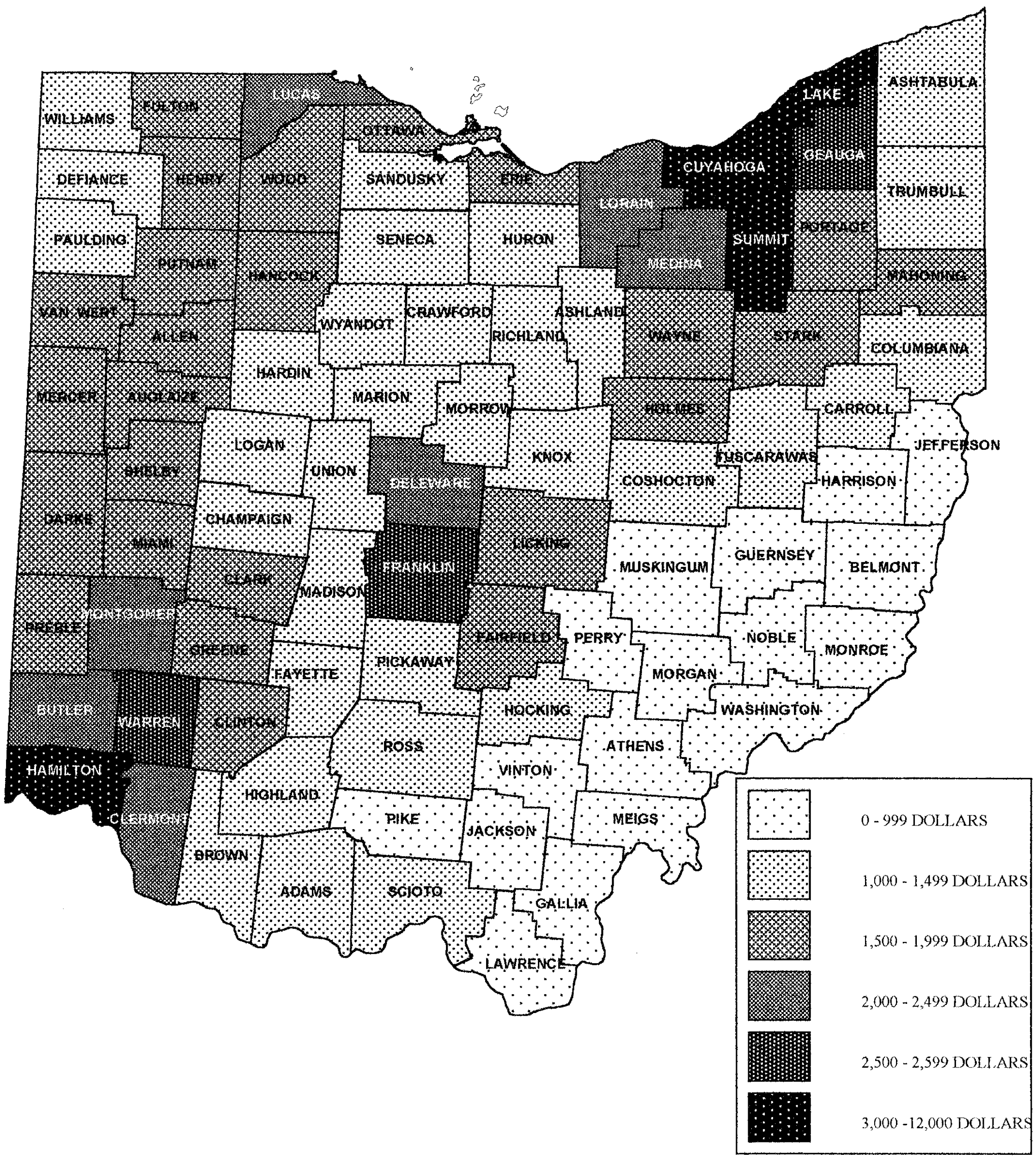


Figure 5.6 Average Market Value of Farm Land and Buildings ($ per acre, 1992)

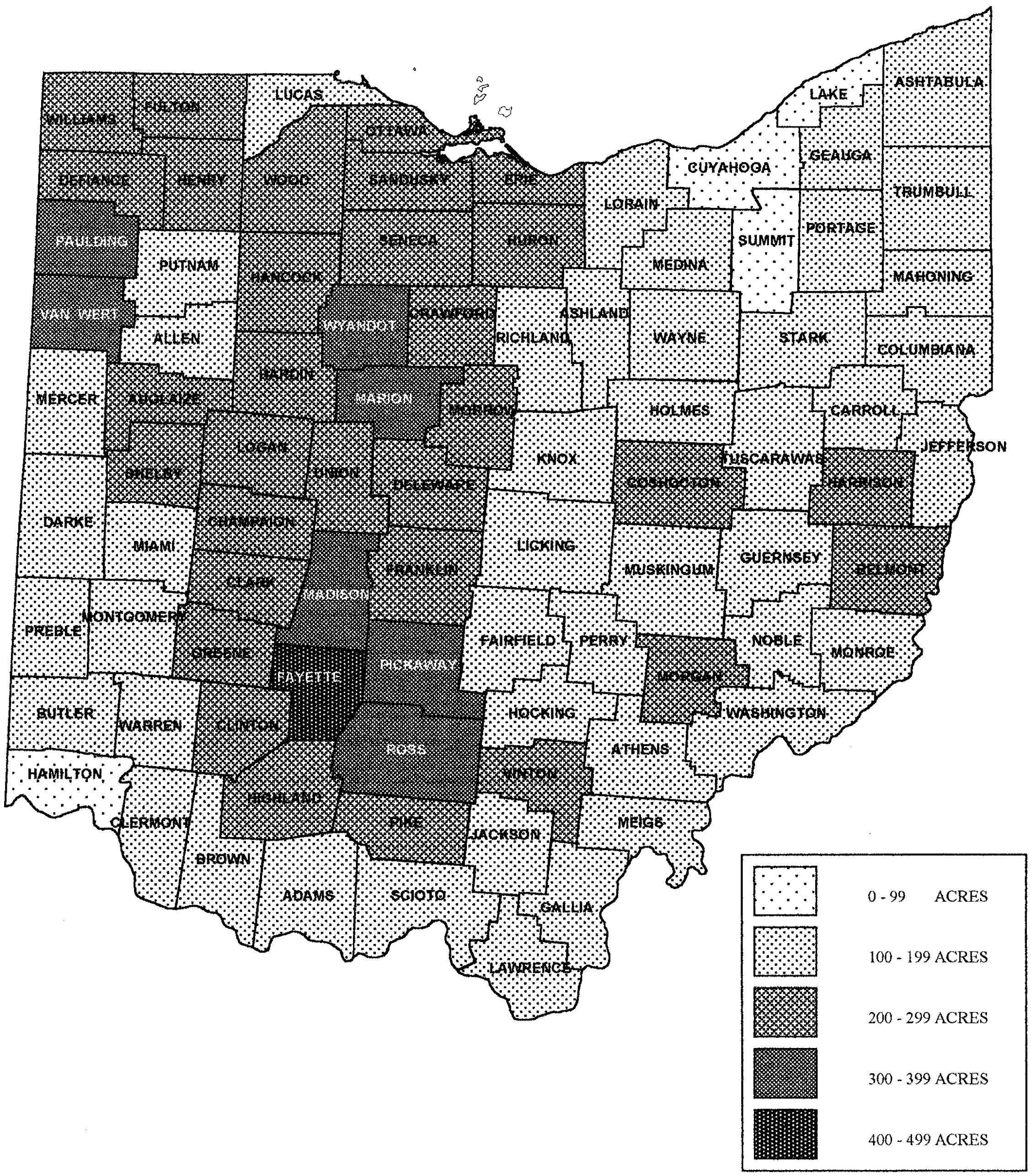


Figure 5.7 Average Size of Farm in 1992

6 SUMMARY AND CONCLUSIONS

6.1 Summary

This project report presents the results of a research program conducted at The Ohio State University from October 1, 1996 to March 31, 2000 to investigate the use of stabilized flue gas desulfurization (FGD) materials in the construction of low permeability liners. The objective of the research program presented in this report was to establish field-verified time-dependent relationships for the performance of liners constructed from stabilized FGD by-products generated in Ohio. The project objective was accomplished with a coordinated program of testing and analyzing small-scale laboratory specimens under controlled conditions, medium-scale wetland mesocosms, and a full-scale pond facility. Although the specific uses directly addressed by this report include liners for surface impoundments, the results presented in this study will also be useful in other applications including design of daily cover and liners for landfills, seepage cutoff walls and trenches and for nutrient retention and pollution mitigation wetlands. The results of this study can provide constructive technical input into the current draft ASTM specification under consideration for use of CCB liners (refer to Appendix B for the text of the ASTM draft specification).

6.1.1 Laboratory Testing Program

Small-scale laboratory permeability, strength, freeze-thaw cycling, leachate potential tests were conducted. Permeability and strength testing were conducted on compacted samples of stabilized

FGD material obtained from two Ohio power plants (Conesville and Gavin). Samples pre-mixed at the power plant and mixed in the laboratory were investigated. The fly ash to filter cake ratio of samples mixed in the laboratory was 1:1 and 2:1 on a dry weight basis. Two lime contents were investigated. The coefficient of permeability for the compacted samples was measured at 7, 28,60, and 90 days of curing using a falling head test procedure. On completion of 90-day permeability test, the samples were tested for unconfined compressive strength. All samples exhibited decreasing permeability with increasing curing time. The addition of extra-lime and fly ash to the laboratory mixed samples resulted in a decrease in permeability of the samples for all curing times especially the 60 and 90-day values (which were reduced by an order of magnitude). The 90-day permeability of high lime content (8%) samples mixed in the laboratory ranged from 10^{-7} cm/sec ($3x10^{-9}$ ft/sec) to 10^{-8} cm/sec ($3x10^{-10}$ ft/sec). The unconfined compressive strength ranged between 1.47 MPa (213 psi) and 3.95 MPa (573 psi) at 90 days of curing. Plant mixed samples had lower permeability coefficient and higher unconfined compressive strength values than laboratory mixed samples. The high lime content (8%) Conesville and Gavin plant mixed samples exhibited permeability values in the 10^{-8} cm/sec ($3x10^{-10}$ ft/sec) range at 28 to 60 days of curing. The strength of the high content lime samples ranged from 4.18 MPa (606 psi) to 4.33 MPa (628 psi). The laboratory permeability and strength testing program showed that quicklime and fly ash enriched stabilized FGD material can be compacted in the laboratory using standard soil testing procedures to obtain permeability coefficients that are in 10^{-8} cm/sec ($3x10^{-10}$ ft/sec) range, which is lower than the 1×10^{-7} cm/sec ($3x10^{-9}$ ft/sec) value typically recommended by USEPA and OEPA for constructing liners for waste containment facilities.

Durability of stabilized FGD material was evaluated in the laboratory as per ASTM D560. The effect of thermal cycling on permeability coefficient of Conesville FGD material was investigated. Samples tested had a fly ash to filter cake ratio of 0.8:1 (typical mix generated at the power plant). Sample lime contents of 4% and 10% (dry weight basis) were investigated. Test cylinders were allowed to cure for 7, 28, 60, and 90 days before being exposed to freeze-thaw cycling. One cycle consisted of a 24-hour of freeze at –18°C, followed by a 24-hour thaw in moist cure box at 23°C. The samples after curing were tested for permeability using the falling head procedure at 0, 5, 10, and 15 freeze-thaw cycles. The permeability coefficient was not significantly affected by the number of freeze-thaw cycles as long as additional water was not added to the sample via an intermediate permeability test. For high lime content samples, in general, addition of moisture during freeze-thaw cycling resulted in increase of permeability coefficient by an order of magnitude. Higher lime content samples exhibited a smaller increase in permeability values due to freeze-thaw cycling coupled with moisture addition. However, curing time of the samples did not significantly affect the permeability coefficients because the fly ash content of the samples was very low and the moisture content (about 60%) was very high. Additional freeze-thaw testing may be necessary at high lime (8-10%) and fly ash to filter cake ratio (2:1) and lower moisture content (about 35-40%).

The leachate potential of five stabilized FGD samples from the Conesville power plant were investigated by conducting USEPA TCLP dilute acetic acid method (Method 1311). Leachates were analyzed for pH, total dissolved solids, acidity, alkalinity, conductivity, and 20 elements by ICP and GFAA spectrophotometry. Leachate concentrations were compared with Ohio EPA non-toxic criteria and national primary and secondary drinking water standards. The leachate data for various constituents studied did not vary over a wide range but was limited to a reasonably small range of values. The measured mean values for all potential contaminants from the FGD leachate were much lower than Ohio EPA non-toxic criteria. Measured leachate concentration levels were consistently lower than the national primary drinking water standards. In general, the concentration of elements in the leachate was also lower than the national drinking water standards expect for pH (mean value of 11.08) and Aluminum (mean value of 5.114 mg/l). The laboratory TCLP testing program conducted on the stabilized FGD material indicates that the stabilized FGD material tested in the laboratory is a relatively clean material, is non-toxic, and poses very minimal risks, if any, for groundwater contamination.

6.1.2 Medium-Scale Mesocosm Experiments

The construction of artificial wetlands for wastewater treatment often requires low permeability clay liners. In this portion of the study, the potential effect of using stabilized FGD in place of clay for constructed wetlands was investigated. The parameters of the study included effect of FGD liner on water quality, plant growth, nutrient composition, and physiochemical investigations of the leachate and surface outflow. In March, 1997 a set of 20 flow-through mesocosms (1 m x 1 m x 0.6 m polyethylene tubs) were positioned at the Olentangy River Wetland Research Park, which is a 22-acre research site located on the Columbus campus of The Ohio State University, to investigate the effect of FGD liner on ecological functions of constructed wetlands. Stabilized FGD by-products were randomly assigned to the mesocosms, which resulted in half of them with no FGD liner in the tubs as control. Mesocosms were completely buried into the ground to insulate against freezing. Each mesocosm received 10 cm of non-calcareous river pea gravel (completely covering the drain to the standpipe) overlain by 10 -15 cm of field compacted stabilized FGD by-product generated from Conesville electric power plant, on top of which 15-20 cm of soil obtained during the excavation of the mesocosm site was placed. The FGD by-product used in the experiment had an estimated fly ash to filter cake ratio of 1.25 :1 and a lime content of 5 %. The FGD by-product placed inn the mesocosms was compacted, but soil (growing medium) was not compacted. A water delivery system was constructed which simulated natural flows of contaminated runoff into natural or constructed wetlands. A continuous inflow rate of 70 ml/minute was chosen as the target inflow rate into each mesocosm. Macrophytes were planted on May 17, 1997. Three *Scirpus tabernaemontani* rhizomes were introduced into each of 20 mesocosms.

Experiments were conducted for several weeks during 1997 and 1998. The 1997 experiment was conducted for four weeks during the growing season (July – August 1997) and for another four weeks in the non-growing season (October, 1997). Three items such as number of stems, number of stems bearing flowers and stem length were investigated weekly on every mesocosm during the growing season experiment and once in the middle of non-growing season. Orthophosphate removal in the leachate was observed to be much more significant in the FGD lined mesocosms than the controls. pH values of leachate for FGD lined mesocosms were higher than controls due to the alkaline nature of FGD. Total phosphorous concentrations were similar for FGD liner and control mesocosms for surface outflow and leachate. No significant differences were measured between Nitrate levels of FGD liner and control mesocosms. Mean stem length and mean number of stems bearing flowers were observed to be lower in the FGD liner mesocosms. This indicated a potential negative impact on plant growth for FGD lined mesocosms, which was investigated further in 1998 through mesocosm productivity through plant harvesting. In 1998, the experiments begun in 1997 were continued but with plants now consisting of a much greater biomass than in the 1997 study. For 1998 investigations, high phosphorous loading was applied to 10 mesocosms, simulating the phosphorous concentration of treated wastewater going to a treatment wetland. Experiments were conducted June through September 1998. In addition to the monitoring carried out in 1997, the above- and below-ground plant biomass was harvested at the end of the experiment for analysis of plant tissue. Soil samples were also taken from the top 5 cm of the soil surface for elemental analysis. FGD lined mesocosms showed much better performance in orthophosphate retention compared to control mesocosms possibly due to Ca-P precipitation. Total phosphorous was more effectively removed from phosphorous spiked surface water passing through FGD lined wetland mesocosms than controls. There was no difference in the above- or below-ground biomass for FGD lined and control mesocosms, although lower average stem length and fewer stem bearing flowers were observed in mesocosms with FGD material as a liner.

6.1.3 Full-Scale FGD-Lined Facility

A full-scale FGD lined facility (capacity of one million gallons) was constructed, in Summer of 1997 at the Ohio Agricultural Research and Development Center (OARDC) Western Branch, South Charleston, to evaluate the performance of a field-compacted FGD liner. The full-scale facility was constructed to addresses two critical questions about the behavior of stabilized FGD products constructed in the field, i.e. what is the permeability of a compacted engineered liner of known thickness and density, and what is the quality of the water that flows through the FGD liner. This OARDC site was chosen over other university sites because it had an abundance of clay onsite that was suitable for use as a secondary or outer liner to contain the primary FGD liner. The OARDC Western Branch facility is a swine and agronomic research facility and, hence, it was decided to build a livestock manure storage facility that could be used by the center for storing swine manure after the completion of the research.

The facility was designed for a capacity of approximately one million gallons to provide six months storage for all liquid wastes from the swine onsite. A double-layered design was chosen with 18 inches of compacted stabilized FGD as the primary inner liner and the onsite clay (about 80 feet of grey glacial till) as the secondary outer liner. A leachate system was designed to be placed between the primary FGD liner and secondary clay liner to collect in a sump any water passing through the FGD fill. The sump was designed so that it could be used to collect leachate samples with ease and for conducting field permeability tests on the pond liner.

Approximately 2,700 tons of lime and fly ash enriched stabilized FGD material from Conesville power plant was used in the construction of the 18-inch primary liner for the full-scale facility. Placement and compaction of FGD in 4-6 inch lifts on top of the geofabric layer were accomplished using two dozers and one sheepsfoot roller. The fly ash to filter cake ratio of the FGD material ranged from 1.48:1 to 2.40:1 with an average ratio of 1.81:1. The lime content varied from 6.79% to 8.44% with an average lime content of 7.98%. The moisture content of the FGD material received at the site during construction ranged from 49% to 62%, while the proctor dry density varied between 9.6 kN/m^3 (61 lb/ft^3) and 11.6 kN/m^3 (74 lb/ft^3). Wet weather during the liner placement resulted in several delays. The site was smooth rolled before completion of the project. The newly constructed facility was filled with water from an existing nearby pond and was completed on September 23, 1997. The pond was filled with water up to a depth of approximately 9 feet. To avoid coring holes in the full-scale FGD liner for obtaining permeability samples, four rectangular FGD test pads were constructed in vicinity of the full-scale facility. Each test pad was initially backfilled with 6 inches of sand to provide a permeable layer for drainage. The remainder of the excavation was filled with stabilized compacted FGD material. Due to the small size of the test pads compared to the plan dimensions of the sheepsfoot roller, adequate compaction of the FGD material in the test pads could not be obtained. Each of the test pad was instrumented for Boutwell field permeability testing apparatuses. The instrumentation and monitoring of the test pads was conducted by BBC & M Engineering of Columbus, Ohio. The actual cash cost of constructing the full-scale facility was estimated to be $46,623.50. The FGD material was made available at the site free of charge by American Electric Power’s Conesville power plant.

The facility was used to store water for the first year. In early September of 1998, some of the water was replaced with swine manure. Since then swine manure has continued to be added and removed from the facility on a regular basis depending on the manure storage vs. field spreading needs of the research farm. Monitoring of the site for field permeability and water quality was carried out for a period of 2 years and 5 months (September 1997 through January 2000). The average monitoring frequency was three months. The monitoring program consisted of two main activities a) field permeability testing and b) water quality monitoring. Field permeability tests were conducted by lowering the water level in the sump to create a head difference across the FGD liner. The amount of time taken to increase the water in the sump to specific levels was observed. Knowing the thickness of the FGD liner and its plan view, the actual effective permeability of the field compacted liner was evaluated. Water quality testing samples were collected from the pond, sump, and a well about 1,000 feet from the site.

Actual permeability coefficients were calculated using the bottom area of the pond as the effective leaching area for the FGD-liner. The full-scale permeability of the facility was evaluated to be 9.1×10^{-7} cm/sec (2.9×10^{-8} ft/sec) at a curing time of one month. The permeability coefficient continued to reduce over time (due to curing of FGD) and has stabilized at approximately 4×10^{-7} cm/sec (1×10^{-8} ft/sec). The FGD permeability coefficient data range obtained from the full-scale tests is comparable to typical clays used in the construction of compacted liners. The full-scale permeability of the field constructed FGD liner includes the effect of freeze-thaw cycling on the actual permeability of the FGD liner. The actual area over which water flows through the FGD liner being greater than the bottom area of the pond, the full-scale permeability values calculated are an upper bound to the actual permeability of the field-compacted FGD liner. The addition of swine manure to the facility (at 370 days of curing and thereafter) did not affect the actual permeability of the liner. If no secondary liner were present at the site, the specific seepage rate for the 9 feet deep manure storage pond having an 18-inch thick FGD liner was calculated to be 0.0952 in^3/in^2/day. Specific seepage rates less than 0.1 in^3/in^2/day are considered to be very low seepage values. It can be concluded that if there was no secondary clay liner constructed for the facility (as would be the norm for typical FGD-lined pond and manure storage facilities), the seepage rate loss from such FGD facilities would be very low.

The actual field permeability data obtained from the full-scale pond tests was compared with a) laboratory tests conducted on laboratory compacted samples collected during pond construction, b) laboratory tests conducted on field compacted samples cored from test pads installed at the site, and c) field permeability tests (Boutwell) conducted on the test pads. All the test procedures showed decreasing permeability coefficient with increasing curing time. It was observed that the laboratory compacted samples had permeability coefficients which were an order of magnitude lower than the full-scale testing values. Permeability values obtained from Boutwell tests and cored samples tested in the laboratory were in close agreement with each other but were one to three orders of magnitude higher than the full-scale tests. The test pad sample permeability values (Boutwell tests and cored sample testing) indicated a large scatter in the data. The test pad permeability coefficients varied from 10^{-4} cm/sec ($3x10^{-6}$ ft/sec) to 10^{-7} cm/sec ($3x10^{-9}$ ft/sec) with average permeability value in range of 10^{-5} cm/sec ($3x10^{-7}$ ft/sec). This may be due to the unsuitable compaction achieved for the test pads. Furthermore, the Boutwell test procedure relates infiltration rate with permeability coefficient by assuming certain direction and boundaries conditions of flow, which are nearly impossible to control in the field. However, it is important to note that the actual measured field permeability values of the full-scale FGD liner are an order of magnitude higher than laboratory measured values.

The water sampling program was conducted while the pond held water (until September 1998) and beyond at which time swine manure was added to the facility on a regular basis (project monitoring ended January, 2000). All samples were tested for several constituents and properties including pH, electrical conductivity, alkalinity, acidity, total dissolved solids, aluminum, arsenic, boron, barium, calcium, cadmium, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorous, lead, sulfur, selenium, silica, silver, vanadium, zinc, chloride, phosphate, sulfate, nitrate, ammonia and nitrogen. The concentration level of various measurements in the sump (leachate) increased suddenly following the filling of the facility with water. Thereafter, the concentration levels reduced rapidly. All the OEPA DSW 0400.007 non-toxic parameters (arsenic, barium, cadmium, chromium, lead, selenium) measured for the FGD facility while holding water and swine manure were much lower than OEPA's non-toxic criteria. For many elements measured (barium, cadmium, chromium, and nitrate) the leachate concentration levels were generally lower than the National Primary Drinking Water Regulations (NPDWR). Arsenic concentration levels for the pond and sump samples were very low for the first year. Upon addition of swine manure to the facility (in early September, 1998), the concentration level of arsenic in the pond increased. However, the sump samples indicate little increase in arsenic concentrations (which are slightly higher than the NPDWR level of 0.05 μg/ml). Arsenic levels in the sump and pond have always been lower than OEPA's non-toxic regulatory value of 1.5 μg/ml. In general, nitrate levels in the leachate are extremely low compared to NPDWR value of 10 μg/ml. The concentrations of highly soluble constituents, such as nitrates and phosphates, were observed to be relatively low in the sump. From a regulatory perspective, the leachate from the FGD material is not required to meet any of the NSDWR limit values, yet the leachate concentration levels measured from the FGD lined facility are generally lower or comparable to NSDWR limits for most potential contaminants of concern.

6.1.4 Cost Estimates and Preliminary Market Evaluation

Cost estimates were prepared for the creation of wetlands and ponds using FGD and clay liners and compared with available published data. In addition, certain macro-features of the potential market for FGD when used as a low permeability liner material were analyzed. For the cost estimates, a consistent data set published by R. S. Means Company, Inc., allowed meaningful comparisons.

Cost estimates were made for a range of alternative haul distances for FGD or clay: 1, 2, 4, 10, 20, and 100 miles round-trip. In addition, the no-cost option for hauling FGD was included to reflect the case wherein no charge is levied by the utility to haul FGD. For a five-acre wetland creation, if the full cost of hauling FGD or clay to the site (by the same haul distance) are included in the cost analysis, the cost savings in using FGD are $19,754, regardless of haul distance. If no cost is assigned to hauling FGD, cost savings increase dramatically with round-trip haul distance for clay. The calculated cost of wetland creation for short haul distances compared well with published literature data.

Cost calculations were also carried out for a water supply / waste water storage pond, If the full cost of hauling FGD to the site is included, the cost savings in using FGD are $3,323 for a 1-mile round-trip but become successively smaller at longer haul distances, and are slightly negative at a 100-mile round-trip. With longer haul distances, the initial cost savings from using FGD can be gradually consumed. If no haul cost for FGD is incurred by the consumer, cost savings are large ($8,396) at a one-mile round-trip and increase steadily as the haul distance increases. The cost estimates for a water supply pond / wastewater lagoon compared reasonably well to available literature data.

A preliminary market study was carried out to obtain an estimate of the possible market size. The market in this case was the number of farms within a reasonable haul time or distance from the power plant. Travel time contours (isochrones) for 15, 30, and 60 minutes from the Conesville and Gavin power plants, as determined from field studies, were constructed. Contours for the Conesville power plant were somewhat wider in geographic coverage than the corresponding ones for Gavin, principally because the highway infrastructure near Conesville is of higher quality. The 60-minute contour for Conesville covered almost an equal number of miles, while that for Gavin covered only about 49 miles. The contour lines were used to determine the area encompassed by them in each county. The Census of Agriculture of 1992 was used to obtain farm density by county. Calculations carried out showed that the density of farms within the 15-minute contour is about the same for the two power plants, but that farm density is much higher at Conesville for the 30 and 60-minute contours. This, coupled with the exclusion of areas outside the state of Ohio, resulted in a much larger market (number of farms) for the Conesville power plant (23, 64, and 221 percent greater for the 15, 30, and 60 minute contours, respectively). Farms comprise a much higher percent of land area near the Conesville plant than near Gavin. In addition, farms near Conesville tend to have a higher market value of land and buildings. The average farm size is about the same in the vicinity of the two plants. Market density, volume, and ability to pay tends to be higher in the vicinity of the Conesville power plant as compared to Gavin.

6.2 Conclusions

A coordinated small-scale laboratory, medium-scale wetland, and full-scale pond testing research program conducted at The Ohio State University for over three years has shown that stabilized FGD materials can be used as low permeability liners in the construction of water and manure holding ponds, and constructed wetlands for wastewater treatment. Actual permeability coefficients in the range of 10^{-7} cm/sec (3×10^{-9} ft/sec) can be obtained in the field by properly compacting lime and fly ash enriched stabilized FGD materials. Leachate from the FGD material meets Ohio's non-toxic criteria for coal combustion by-products, and for most potential contaminants the national primary and secondary drinking water standards are also met. The low permeability non-toxic FGD material investigated in this study poses very minimal risks, if any, for groundwater contamination. Constructed FGD-lined wetlands offer the opportunity for increased phosphorous retention giving rise to the potential use of these materials as a liners for wastewater treatment wetlands. While plant growth was observed to be less vigorous for FGD lined wetland mesocosms compared to the control, the above and below ground biomass were not significantly different. Cost estimates for FGD liners compared favorably with clay liners for varying haul distances.

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8 APPENDICES

Appendix A

List of Technical Publications and Presentations, and Publicity Articles

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Conference Proceedings and Presentations

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Coal Alternative for Waste-Lagoon Lining, AG Answers, Purdue University, September 3, 1997

Coal Byproduct Used in Waste Lagoons, Farm and Dairy, September 11, 1997

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Coal Byproducts Promising as Lining in Livestock Waste Lagoons, Ohio Country Journal, September 1997

Waste Not, Want Not, Ohio State Agriculture, Fall/Winter, 1997

Coal By-Product Possible For Lagoon Liners, Illinois AgriNews, October 24, 1997

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Poster at Swine Day, OARDC-Western Branch, South Charleston, Ohio, September 3, 1998

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Appendix B

Draft ASTM Specification for CCB Liners (12/11/97)

ASTM Designation:

Standard Guide for

Use of Coal Combustion Products for Low Permeability Barriers, Liners, and Encapsulations

This standard is issued under the fixed designation ___________; the number immediately following the designation indicates the year of original adoption.

1 Scope

1.1 This Guide addresses procedures for the design and construction of low permeability barriers, liners, and encapsulations using Coal Combustion Products (CCPs) and mixtures thereof.

1.2 The utilization of CCPs under this guide is a component of a pollution prevention program; Guide E 1609 describes pollution prevention activities in more detail. Utilization of coal combustion products in this manner conserves land, natural resources, and energy.

1.3 This guide provides general guidelines for CCPs produced primarily from the combustion of coal. Where appropriate, guidelines specific to different types of CCPs (fly ash, bottom ash, stabilized flue gas desulfurization material) are included.

1.4 The testing, engineering, environmental, and construction practices for CCP barriers are similar to generally accepted practices for natural soil barriers. Specific practices are included for cementitious and stabilized CCPs. CCP barriers, liners, and encapsulations should be designed in accordance with generally accepted engineering practices.

1.5 Laws and regulations governing the use of CCPs vary by state. The user of this standard has the responsibility to determine and comply with applicable requirements.

1.6 The values stated in SI units are to be regarded as the standard. English units are given in parentheses are for information only.

1.7 This standard does not purport to address all safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2 Referenced Documents

2.1 ASTM Standards

C25 Standard Test Method for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime

C311 Sampling and Testing Fly ash or Natural Pozzolans for Use as A Mineral Admixture in Portland-Cement Mixtures.
C305 Standard Method for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency.
C472 Test Methods for Physical Testing of Gypsum, Gypsum Plasters, and Gypsum Concrete
C593 Specification for Fly Ash and other Pozzolans for Use with Lime
C617 Standard Practice for Capping Cylindrical Concrete Specimens
C702 Standard Practice for Reducing Field Samples of Aggregate to Testing Size
C75 Practice for Sampling Agggregates
D653 Standard Terminology Relating to Soil, Rock and Contained Fluids
D698 Standard Testing for Moisture-Density Relations of Soils and Soils-Aggregate Mixtures 5.5 lb (2.49 -kg) Rammer and 12 in. (305-mm) Drop
D1140 Test Method for Amount of Material in Soils Finer than the No. 200 Sieve
D427 Test Method for Shrinkage Factors of Soils by the Wax Method
D4943 Test Method for Shrinkage Factors of Soils by the Mercury Method
D1556 Standard Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method
D1557 Standard Test Method for Laboratory Compaction Characteristics of Soils using Modified Effort
D1635 Test Method for Flexural Strength of Soil-Cement Using Simple Beams with Third-Point Loading
D2166 Standard Test Methods for Unconfined Compressive Strength of Cohesive Soil
D2216 Laboratory Determination of Water (Moisture) Content Soil, and Rock
D2167 Standard Test Method for Density and Unit weight of Soils in Place by the Rubber Balloon Method
D2487 Classification of Soils for Engineering Responses (Unified Soil Classification System)
D3080 Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions
D3282 Classification of Soils and Aggregate Mixtures for Highway Construction Purposes
D3987 Test Method for Shake Extraction of Solid Waste with Water
D4318 Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
D 4767 Test Method for Consolidated-Undrained Triaxial Compression Tests on Cohesive Soils
D2922 Test Methods for Density of Soil and Soil Aggregates in Place by Nuclear Methods (Shallow Depths)

2.2 Other Methods

United States Army Corp of Engineers, EM 1110-2-1906 Falling Head Permeability Test
United States Army Corp of Engineers, EM 1110-2-1906, App. VII Constant Head Permeability Test
U.S. EPA Method SW-846 Method 9081 Cation-Exchange Capacity of Soils

3 Terminology

3.1 Definitions - Definitions are in accordance with Terminology D 653.

3.2 Descriptions of Terms Specific to This Standard:

3.2.1 beneficial reuse - projects promoting public health and environmental protection, offering equivalent success relative to other alternatives, and preserving natural resources.

3.2.2 binder - anything that provides or results in cohesion or cementitious properties in loosely assembled substances, such as clay or cement.

3.2.3 bottom ash - agglomerated ash particles formed in pulverized coal boilers that are too large to be carried in the flue gases and that impinge on the boiler walls or fall through open grates to an ash hopper at the bottom of the boiler. Bottom ash is typically grey to black in color, angular and has a porous surface texture.

3.2.4 cation - an ion that moves, or would move, toward a cathode, thus nearly always synonymous with positive ion.

3.2.5 cation exchange capacity (CEC) - a measurable amount of potential for holding the exchange of positively charged ions resulting from dissociation of molecules in solution (leachate) with the CCP barrier.

3.2.6 coal ash - material produced from the combustion of coal.

3.2.7 coal combustion products - fly ash, bottom ash, boiler slag, or flue gas desulfurization (FGD) material resulting primarily from the combustion of coal.

3.2.8 coefficient of permeability - the rate of discharge under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions (20oC).

3.2.9 encapsulation - the complete enclosure of a material in another material in such a way as to isolate it from external effects such as those of water or air.

3.2.10 fixation - a physical immobilizing of particulates achieved by development of chemical cementitious bonds.

3.2.11 flexural strength - the maximum load sustained by a standard specimen of a sheet material when subjected to a bending force.

3.2.12 flue gas desulfurization material - (FGD) material products resulting from sulfur dioxide removal from combustion emissions. Stabilized FGD is produced from the mixture of lime, fly ash, or other binder to produce products such as synthetic gypsum.

3.2.13 fluidized bed combustion ash - (FBC) a fly ash produced from the combustion of coal in a fluidized bed combustion unit.

3.2.14 fly ash the finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the firebox through the boiler by flue gases.

3.2.15 fly ash to flue gas desulfurization material ratio - a ratio of the amount fly ash to FGD material calculated on a dry weight basis.

3.2.16 guide - a series of options or instructions that do not recommend a specific course of action. Discussion: Whereas a practice describes a general usage principle, a guide only suggests an approach. The purpose of a guide is to offer guidance, based on a consensus of viewpoints, but not to establish a fixed procedure. A guide is intended to increase the awareness of the user to available techniques in a given subject area and to provide information from which subsequent evaluation and standardization can be derived.

3.2.17 hydraulic conductivity - see definition for coefficient of permeability.

3.2.18 liquefaction - The process of transforming any material from a solid state to a liquid state, usually as a result of increased pore pressure and reduced shearing resistance.

3.2.19 optimum density - the maximum density obtainable in the laboratory using a specific compactive effort and while varying the material moisture content.

3.2.20 pozzolans siliceous or siliceous and aluminous materials that in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

3.2.21 practice - a definitive procedure for performing one or more specific operations or functions that does not produce a test result. Discussion: A practice is not a downgraded test method. Examples of practices include procedures of interlaboratory testing programs or other statistical procedures; for writing statements on sampling or precision and accuracy; and for selection, preparation, application, inspection, necessary precautions for the use, disposal, installation, maintenance, and operation of testing equipment.

3.2.22 quicklime - a lime oxide formed by calcining limestone so that carbon dioxide is liberated. It may be high calcium, magnesium, or dolomitic of varying degrees of chemical purity.

3.2.23 stabilization - The conversion of a material from it's original form to a physically and chemically more stable material. Stabilization typically includes chemical reactions that generate products that are less volatile, soluble, and reactive.

3.2.24 standard - as used in ASTM, as document that has been developed and established within the consensus principles of the Society and that meets the approval requirements of ASTM procedures and regulations. Discussion: the term "standard" serves in ASTM as an adjective in the title of documents such as test methods or specifications, to connote specified consensus or approval. The various types of standard documents are based on the needs and usages as prescribed by the technical committees of the Society.

3.2.25 thixotropic - material which exhibits the property of thixotropy.

3.2.26 thixotrophy - the property of a material that enables it to stiffen in a relatively short time on standing, but, upon agitation or manipulation, can change to a very soft consistency or to a fluid of high viscosity, the process being completely reversible.

4 Significance and Use

4.1 General - Coal combustion products (CCPs) can be used effectively for the construction of engineered low permeability barriers, liners, and encapsulations. CCP's may be used as caps, liners or barriers, for landfills, storm water runoff basins, and other applications requiring a barrier to minimize fluid migration. CCPs low permeability, relatively low unit weight, compressive strength, flexural strength, ion exchange capability, and uniform properties make it an effective barrier material. Also, because CCPs are abundantly produced products, they are readily available for large volume applications. Use of CCPs encourages the preservation of natural materials and minimizes the environmental impact associated with the acquisition of conventional barrier materials.

4.1.1 Compatibility of Liner Product and Infiltrate - A primary concern in the selection and the ultimate performance of a barrier is it's compatibility characteristics with the leachate of the material it is isolating from the environment. The issue of compatibility focuses on barriers, and liners rather than surface encapsulations since the potential for adverse chemical interactions is much greater. The compatibility of a liner is dependent on many variables which can alter a CCP liner's coefficient of permeability. US EPA SW846 Method 9100 can be used to evaluate a CCP's compatibility. Laboratory tests should be performed to evaluate this relationship on a case specific basis.

4.1.2 Expansion and Shrinkage - CCP's generally exhibit little shrinkage if placed at the optimum density. Expansion is a concern for CCPs that are produced from fluidized bed combustion units (FBC). CCPs from some FBC units are known to have greater expansion potential than CCPs generated from pulverized coal units. Laboratory testing of CCPs can be used to determine the expected extent of expansion and shrinkage.

4.2 Engineering Properties and Behavior

4.2.1 Alternatives for Conventional Materials - Conventional materials such as clays or synthetic plastics have been used for low permeability barriers. Materials typically used for landfill barriers are required to have a coefficient of permeability equal to or less than 1x10-7 cm/sec. CCP liners can achieve coefficient permeability values in the same order of magnitude and in addition offer other physical and operational benefits.

4.2.2 Coefficient of Permeability - The coefficient of permeability for synthetic barriers utilizing plastics are typically less than 1x10-9 cm/sec. Natural soils such as liner grade clays range from 1x10-6 cm/sec to 1x10-9 cm/sec. Liner grade CCPs range from 1x10-6 cm/sec to 1x10-7 cm/sec. Stabilized and pozzolanic CCP barriers develop a low coefficient of permeability as a result of compaction and chemical fixation or curing. Stabilized CCPs ultimate permeability levels are not achieved upon placement but after the cementitious chemistry progresses, usually within 30 to 60 days.

4.2.2.1 State agencies that currently recognize and permit the use of these materials in liner construction recognize the difficulties in collecting undisturbed representative samples for testing and therefore require additional Quality Assurance/Quality Control (QA/QC) procedures. A QA/QC program is necessary to insure the production and placement of material is conducted in a manner that the materials perform as determined in the laboratory.

4.2.3 Flexural Strength - Liner materials typically are required to allow a certain amount of settlement. CCPs exhibit consistent flexural strength and can be designed to accommodate predicted settlement.

4.2.4 Ion Exchange Capacity - Regulatory programs may require containment systems for waste disposal facilities to exhibit some degree of cation exchange capability. Water in time will migrate through most barrier materials. Leachate above a liner may have dissolved cations (e.g. lead, or iron) which can be captured from the water medium passing through the barrier if the barrier has cation exchange capacity. A similar phenomenon is anion exchange (e.g. sulfates, iron, chlorides, and borates). Stabilized FGD barriers typically exhibit a cation exchange capacity which conforms to regulatory requirements. The anion ion exchange capacity for CCPs is typically in excess of two magnitudes higher than clay minerals.

4.2.5 Erosion potential - CCPs vary in their ability to resist erosion. Bottom ash, boiler slag, and Stabilized FGD materials which have been properly placed and compacted according to good engineering practice can be resistant to wind and rain erosion. Fly ash materials are generally highly erodible and require a protective cover. CCP liners exposed to water wave action typically require additional protection. CCP barriers that are designed with binders or additives, such as quicklime, develop shear, compressive, and flexural strength from the mineralogical phase change. The cured material exhibits a low liquefaction potential and generally is resistant to erosion and useful for controlling stormwater runoff quality.

4.3 Environmental Consideration

4.3.1 Regulatory Framework

4.3.1.1 Federal The U.S. Environmental Protection Agency (USEPA) has completed a study of CCPs for the U.S. Congress and has issued a formal regulatory determination (1,2). EPA "encourages the utilization of coal combustion byproducts and supports state efforts to promote utilization in an environmentally beneficial manner" (3). There currently are no regulatory requirements at the federal level on the use of CCPs.

4.3.1.2 State and Local There is considerable variation in state and local regulati ons. Regulatory requirements in most states have specific barrier provisions.

4.4 Economic Benefits - The use of CCPs as low permeability materials can have economic benefits. These benefits are affected by local and regional factors including: production rates, processing and handling costs, transportation costs, availability of competing materials, environmental concerns, and the experience of materials specifiers, design engineers, purchasing agents, contractors, legislators, regulators, and other professionals. In many areas CCPs are available in bulk quantities. Use of CCPs reduces the expenditures for the purchase, permitting, and operation of a soil borrow pit and the associated environmental impact.

5 <u>Laboratory Test Procedures</u>

5.1 General - Laboratory testing of the barrier materials is needed to determine and confirm material properties for design. Test results also provide documentation that may be requested or required by site owners and regulatory agencies. The tests to be conducted should be determined based on site conditions, knowledge of the CCPs, end use, and local environmental considerations. Laboratory testing procedures should account for changes in properties over time as CCP material cures and gains strength.

5.2 Sampling - a sampling protocol is recommended that ensures representative samples are collected of the CCP for quality control of the CCP source, and to verify proper placement of material.

5.2.1 Bulk Sampling - Two recommended ASTM sampling procedures for bulk sampling of CCPs are C311 and C702.

5.2.2 Sampling and Handling Sampling CCPs for testing purposes should conform to Practice D 75 or Test Method C 311 as appropriate. Sampling of in-place CCPs should consider ASTM D 420 for site characterization and D1452, D1586, or D3550 for sampling methods. Proper laboratory protocols for handling fine material should be followed.

5.3 Physical and Engineering Characteristics Standard tests developed for soils may be used to determine CCP properties for use in CCP barriers. Test methods include ASTM D 2487, D 3282, D 4318, and D2216. These methods define physical and engineering parameters for use in design, construction control, and for comparison to other materials.

5.3.1 Coefficient of Permeability - United States Army Corps of Engineers, EM 1110-2-1906 Falling Head Permeability Test, or EM 1110-2-1906, App. VII Constant Head Permeability Test can be used.

5.3.2 Compaction - Test method D 698 or D 1557 may be used to determine the relationship between water content and dry unit weight of CCP and to establish the maximum dry density for the CCP material. For non-cementitious CCPs testing can be performed as the material is placed. For cementitious CCPs the time interval between placement and testing in the laboratory should account for the influence of the rate of hydration on compaction characteristics. Compaction criteria should consider the thixotropic properties of uncured stabilized FGD material because of the potential for liquefaction due to excess vibration. The tests recommended for in-place density testing are D 2167, D 2922, and D1556.

5.3.2.1 Optimum Density - ASTM Standard D 698 or D 1557 are used depending on the specified compactive effort.

5.3.3 Strength - A CCP's material properties can be defined by shear strength, flexural strength, and compressive strength. Fly ash and stabilized FGD material typically develop additional strength through a mineralogical phase change resulting from the pozzolanic reaction which occurs over time. Testing of pozzolanic CCPs should be conducted on samples that have been cured at different intervals to determine the strength gain over time.

5.3.3.1 Shear Strength - Test Method D 3080 can be used to determine the shear strength parameters of compacted CCP specimens for drained conditions. Test Method D 4767 can be used to determine the shear strength parameters for undrained conditions.

5.3.3.2 Flexural Strength - Test Method D 1635 Standard Method for Flexural Strength of Soil-Cement Using Simple Beam with One-Third-Point Loading is used to determine flexural strength of cured CCPs.

5.3.3.3 Compressive Strength - Test Method D 2166 can be used to determine the unconfined compressive strength at various stages of curing to evaluate short-term and long-term strength development. C 617 Standard Practice for Capping Cylindrical Concrete Specimens is used in conjunction with the above standard in preparation of samples.

5.3.3.4 Ion Exchange Capacity - U.S. EPA Method SW-846 Method 9081 Cation-Exchange Capacity of Soils is used for determining the cation exchange capacity for CCP barriers or D 4943.

5.3.3.5 Shrinkage and Expansion - Test method D 427 can be used to determine the shrinkage properties of CCPs. Test method D 4829 can be used to determine the expansive properties of CCPs.

5.4 Production Quality Control for Stabilized FGD Material

5.4.1 General - Testing during production of stabilized FGD material is recommended to ensure that proper proportions of materials are maintained. This section includes suggested parameters.

5.4.2 Water Content - (% solids) Test Method D 2216 is recommended for determining the water content of stabilized FGD material. The drying temperature should be lowered to 60oC (140oF) to avoid driving off the water of hydration. ASTM Test C 472 can also be used when testing synthetic gypsum and similar materials produced from stabilized FGD material.

5.4.3 Fly ash to FGD Material Ratio - After the determination of optimum water content, a completely dried sample of the barrier material mixture is tested to determine total fly ash content. The ratio of fly ash to FGD material is then calculated on a dry weight basis.

5.4.4 Binder - C 25 Standard Test Method for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime can be used to determine the total amount of binder.

6 <u>Design Considerations</u>

6.1 General - A barrier should be constructed to provide the required amount of material isolation from the surrounding environment as established by the user and other regulatory requirements. Before the design of a barrier can begin, it is necessary to review all federal, state, and local regulations. The regulations address standards to which the barrier must conform. These standards can include, but are not limited to, the permeability coefficient, thickness, and integrity of construction.

6.2 Design Specifications - Specifications should define the properties, preparation, placement, testing and performance of CCP's used in barriers. Barriers constructed of stabilized FGD material or CCPs with natural pozzolanic properties will develop different strengths and permeability values depending on the mix design, production, placement, and time of curing. A quality control program is recommended to ensure that materials used for barrier construction satisfy the requirements of the specification. For all CCPs, specifications should include requirements for subgrade preparation, in-place density, allowable range of water content, lift thickness, cover material, and field testing frequency. In addition for stabilized FGD materials, specifications should include allowable material ratios and the amount of stabilizing agent or other binders required. A test pad may be used to demonstrate construction specifications and verify lab based permeability predictions.

6.2.1 Requirements for Stabilized FGD and Other Pozzolanic Materials

6.2.1.1 Optimization of Mix Design - The optimum mixture of CCP, water, and binder (if needed) shall be determined by varying the ratios of the different components and testing for the material properties. Once the optimum mixture is determined, allowable component ranges which produce acceptable material properties are determined.

6.2.1.2 Quality Control Plan and Quality Assurance Plan (QA/AC) - This guide recommends that specific plans to be followed after the optimum mix designs are determined: a Quality Control Plan for the production of the CCPs, and a Quality Assurance Plan for the construction of the CCP barrier. The nature of barrier constructed using pozzolanic material, specifically that it's properties improve with time (typically requiring a curing period of up to 60 days), precludes using in-place testing alone to verify material properties meet specified values. Implementing a

QA/QC plan ensures that the performance of the barrier will exhibit the properties predicted in the laboratory.

7 Construction

7.1 General - Construction procedures for CCP barriers are similar to conventional earthwork operations. Routine methods employed with soil barriers to control dusting, erosion, and sedimentation are similarly required. When binders such as quicklime are mixed in-place additional environmental precautions maybe required.

7.2 Construction Controls

7.2.1 Site Preparation The subgrade should be stripped of vegetation and organic soils. The subgrade should be compacted to the specified density.

7.2.2 Placement and Compaction - CCPs should be placed and spread in uniform layers not exceeding the thickness specified. Tracking the CCPs with a bulldozer or truck can provide a portion of the compactive effort. Typically use of a vibratory or pneumatic tired roller is necessary to achieve the required density. CCP materials should not be placed on saturated or frozen material. Water added to adjust the CCP moisture content should be applied uniformly. Compaction should be completed after adequate time is allowed for the entire lift to equilibrate but before the surface of the material dries.

7.2.3 Erosion Control - CCPs typically do not require additional sedimentation and erosion control measures beyond those normally employed for soil barriers to comply with state and local requirements.

7.2.4 Weather Restrictions - Construction should be suspended during severe weather conditions. Operations may proceed during moderately wet periods by reducing the amount of water added to compensate for precipitation. Barrier construction should not be conducted during temperatures below freezing. When unprotected material is exposed to freezing temperatures, the material should be removed to the depth of frost penetration. After thawing, the frozen material typically may be reincorporated into the barrier construction.

7.2.4.1 In various areas of the country, the daily mean air temperatures may fall below freezing for significant period of time during the winter. It is important to adequately protect a CCP barrier from freeze/thaw cycling effects. As with any constructed barrier, placing a protective soil cover or insulating material on top of the constructed barrier ensures that no deterioration will occur from freeze/thaw cycling. Typically, materials contained by the barrier can be shown to provide the required protective insulation.

7.2.4.2 Stabilized CCPs - The effect of temperature on rate of strength gain should be considered during cooler temperatures. The hydration reaction and associated strength gain will continue at temperatures above freezing and will accelerate as temperatures rise.

7.2.5 Dust Controls - As with conventional materials CCPs when exposed to the elements and allowed to dry, are susceptible to dusting. Dust control measures routinely used on earthwork projects are effective in minimizing airborne particulates. Typical controls include appropriate hauling methods, use of wind breaks, moisture conditioning of the CCP, wetting or covering of exposed CCP surfaces, chemically treating CCP surfaces and paving, wetting, and covering of high traffic haul roads with non-dusting materials.

7.2.6 Requirements for Stabilized FGD and Other Pozzolanic Materials

7.2.6.1 Field Implementation of the Quality Assurance Program - A stabilized CCP barrier's expected performance level is not achieved until it has undergone adequate curing. To ensure that the material will perform as designed in the laboratory, strict adherence to a QA plan is recommended. Representative sampling of the CCP material is collected as it is placed during barrier construction. Laboratory testing is used to verify that the material is produced according to design specifications, and determines the optimum density at which the uncured CCP materials must be placed. In place density testing can be conducted on the CCP barrier to ensure curing conditions meet those defined in the specifications. An additional layer of CCP barrier material can be used as a protective cover to ensure optimum conditions are maintained for curing the primary barrier layer. The QA plan should specify the frequency and quantity of laboratory testing required.

8 Keywords

8.1 Flue Gas Desulfurization materials, liners, coal ash, coal combustion products, barrier, utilization, pollution prevention, beneficial reuse

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Appendix C

Field Permeability Testing at The Proposed Waste Lagoon at OARDC Western Branch, South Charleston, Ohio (Prepared by William L. Broskey, P.E., BBC & M Engineering, November 24, 1997)